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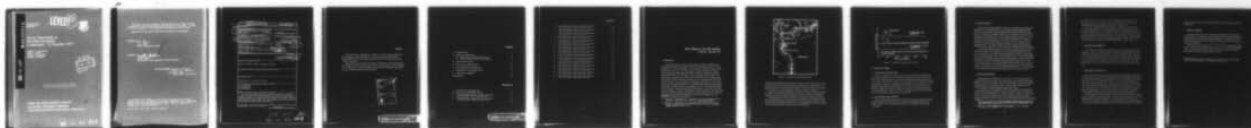
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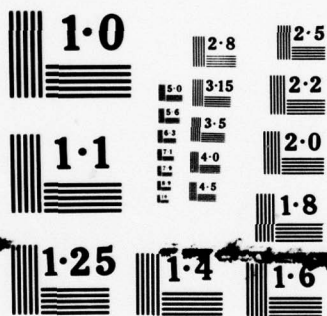
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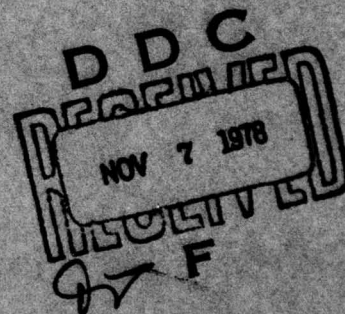
RADC-TR-78-95
IN-HOUSE REPORT
APRIL 1978

LEVEL *2*



**VLF/LF Reflectivity of
the Polar Ionosphere
4 September - 31 December 1977**

ROBERT P. PAGLIARULO
JOHN P. TURTLE
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**ROME AIR DEVELOPMENT CENTER
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Preface

The authors thank in particular Dr. Edward A. Lewis for valuable discussions on preparing this paper, SSgt Robert L. Cooley for data preparation, and Mr. Bjarne Ebbesen of the Danish Meteorological Institute for the outstanding operation at Qanaq, Greenland.

Appreciation is also extended to the Danish Commission for Scientific Research in Greenland for allowing these measurements to be conducted and to Jorgen Taagholt and V. Neble Jensen of the Danish Meteorological Institute's Ionospheric Laboratory for their continued cooperation in this program.

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Contents

1. INTRODUCTION	7
2. OBSERVED WAVEFORMS	9
2.1 Weekly Example of Individual Waveforms	9
2.2 Three-Dimensional Waveform Presentation	9
3. REFLECTION HEIGHTS	10
4. REFLECTION COEFFICIENTS	10
5. SUPPLEMENTARY INFORMATION	11
6. IONOSPHERIC DISTURBANCE DATA	11
7. ADDITIONAL COMMENTS	12
REFERENCES	13

Illustrations

1. Geometry of the Propagation Path	8
2. Examples of the Observed Waveforms	9
3. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 247 (4 Sep) - DAY 253 (10 Sep) 1977	14
4. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 254 (11 Sep) - DAY 260 (17 Sep) 1977	18

Illustrations

5. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 261 (18 Sep) — DAY 267 (24 Sep) 1977	22
6. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 268 (25 Sep) — DAY 274 (1 Oct) 1977	26
7. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 275 (2 Oct) — DAY 281 (8 Oct) 1977	30
8. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 282 (9 Oct) — DAY 288 (15 Oct) 1977	34
9. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 289 (16 Oct) — DAY 295 (22 Oct) 1977	38
10. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 296 (23 Oct) — DAY 302 (29 Oct) 1977	42
11. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 303 (30 Oct) — DAY 309 (5 Nov) 1977	46
12. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 310 (6 Nov) — DAY 316 (12 Nov) 1977	50
13. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 317 (13 Nov) — DAY 323 (19 Nov) 1977	54
14. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 324 (20 Nov) — DAY 330 (26 Nov) 1977	58
15. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 331 (27 Nov) — DAY 337 (3 Dec) 1977	62
16. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 338 (4 Dec) — DAY 344 (10 Dec) 1977	66
17. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 345 (11 Dec) — DAY 351 (17 Dec) 1977	70
18. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 352 (18 Dec) — DAY 358 (24 Dec) 1977	74
19. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 359 (25 Dec) — DAY 365 (31 Dec) 1977	78

VLF/LF Reflectivity of the Polar Ionosphere

4 September - 31 December 1977

1. INTRODUCTION

This paper provides a summary of high latitude ionospheric reflectivity, as observed by the USAF's high resolution VLF/LF ionosounder operating in northern Greenland.^{1,2} As shown in Figure 1, the transmitter is located at Thule Air Base, Greenland (76° 33'N. Lat., 68° 40'W. Long.), and the receiving site is 106 km north at the Danish Meteorological Institute's Ionospheric Observatory in Qanaq, Greenland (77° 24'N. Lat., 69° 20'W. Long., Geomagnetic Lat. 89° 06'N). The ionosounding transmissions consist of a series of extremely short (approximately 100 μ sec) VLF pulses, precisely controlled in time, and radiated from a 130 meter vertical antenna. At the receiving site, orthogonal loop antennas are used to separate the two polarization components of the ionospherically reflected skywave signal. One antenna, oriented in the plane of propagation, is used to sense the groundwave and the "parallel" component of the downcoming skywave. The second loop, nulled on the groundwave, senses the "perpendicular" skywave component. The signal from each of the antennas is digitally averaged to improve the signal-to-noise ratio of the individual received waveforms before they are recorded on magnetic tape. An

(Received for publication 25 April 1978).

1. Lewis, E. A., Rasmussen, J. E., and Kossey, P. A. (1973) Measurements of ionospheric reflectivity from 6 to 35 kHz, J. Geophys. Res. 78:19.
2. Kossey, P. A., Rasmussen, J. E., and Lewis, E. A. (1974) VLF pulse ionosounder measurements of the reflection properties of the lower ionosphere, Akademie Verlag, COSPAR, July.

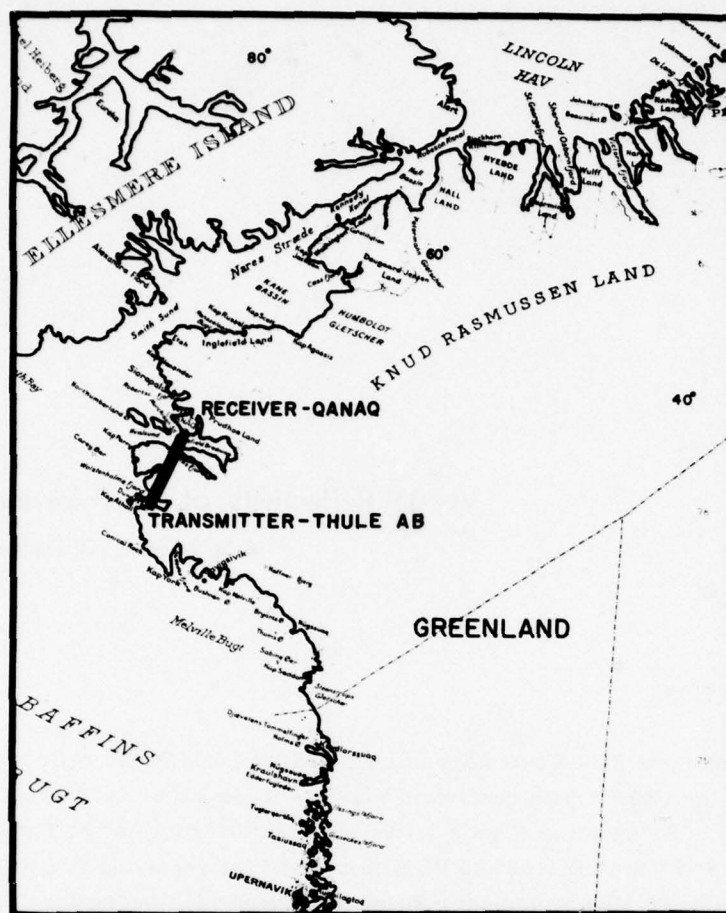


Figure 1. Geometry of the Propagation Path

example of the observed waveforms is given in Figure 2, where the "parallel" waveform (Figure 2a) consists of a groundwave propagated pulse, a quiet interval containing low level, off path groundwave reflections, followed by the first-hop parallel skywave component. The perpendicular waveform is shown in Figure 2b.

Ionospheric reflection parameters are derived by computer (AFGL's CDC 6600) processing of the ground and ionospherically reflected waveforms with allowance made for factors such as ground conductivity and antenna patterns (see Section 4).

Although the data are recorded about once per minute, for this paper the waveforms are averaged into two-hour time blocks with the exception of the three-dimensional waveform presentations (Section 2.2). The resulting information is presented in a weekly format (Figures 3 through 19) as described below.

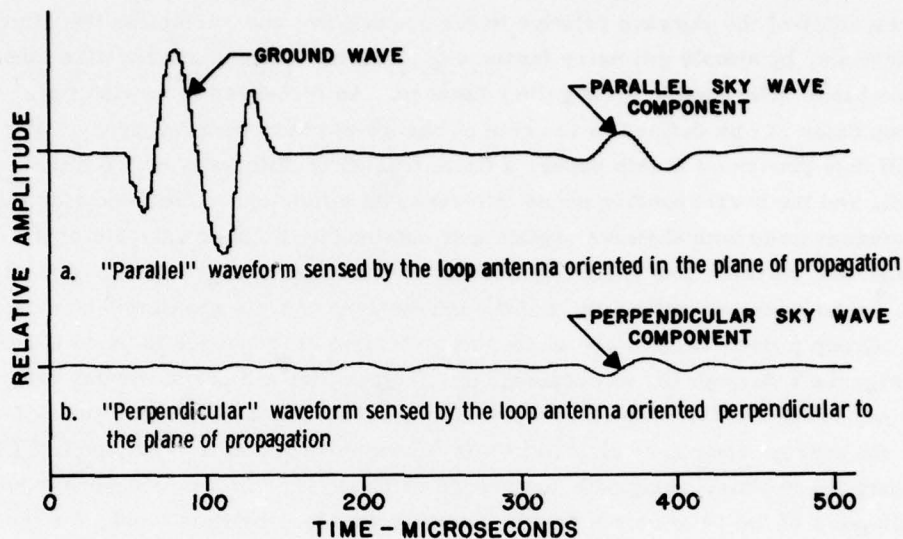


Figure 2. Example of the Observed Waveforms

2. OBSERVED WAVEFORMS

2.1 Weekly Example of Individual Waveforms

In part A of Figures 3 through 19 a set of averaged parallel and perpendicular waveforms is presented for the time block centered near local noon of the indicated day. Each of these waveforms is comprised of 256 digitally averaged points spaced $2 \mu\text{sec}$ apart. In part B of the figures, the groundwave Fourier amplitudes are shown as a function of frequency. Although the data presented in parts C through L of the figures are generally limited to frequencies in the first, or principal, lobe of the spectrum, information at higher frequencies can be used when sufficient signal-to-noise conditions exist. There is, however, a frequency range around each spectral null where insufficient signal exists for measurements.

2.2 Three-Dimensional Waveform Presentation

A three-dimensional display of the recorded \parallel waveforms covering each weekly period is shown in Part R of each figure and the corresponding \perp waveforms are shown in Part S. For these plots the data has been averaged into fifteen minute time blocks.

3. REFLECTION HEIGHTS

The group mirror height (GMH) of reflection was obtained by determining the group delay of the skywave relative to the groundwave and attributing this time difference, by simple geometry (assuming a sharply bounded mirror-like ionosphere) to a difference in propagation distance. As discussed in Lewis et al,¹ the group delay can be defined as the rate of change of phase with frequency. For the GMH data presented in this paper, a finite frequency difference of 1.0 kHz was used, and the corresponding phase difference as a function of frequency for the groundwave and both skywave signals was obtained by Fourier analysis of the respective pulses. The GMH calculations took into account ground conductivity (10^{-3} mho/meter is assumed), and the corrections of Wait and Howe³ were applied.

Group mirror heights are plotted as a function of frequency in parts C and D of Figures 3 through 19, as obtained from the parallel and perpendicular waveforms, respectively. The GMH's are also presented as a function of time-of-day for the average frequency of 16.5 kHz in figure parts E and I. The parallel GMH's in part E are shown along with an average reflection height for reference purposes. Each point of the reference height is a weekly average, by time block, for the 7-day period indicated. The corresponding perpendicular GMH's, part I of the figures, are also shown with the weekly average for comparison. Part G gives the average, by time block, for the daily parallel GMH data of part E, and part K gives the corresponding perpendicular GMH averages from the daily data of part I.

4. REFLECTION COEFFICIENTS

Assuming that the ionosphere acts as a "mirror" at the GMH, plane wave reflection coefficients⁴ were obtained by comparing the ratio of the skywave Fourier amplitude at a specific frequency to that of the groundwave, taking into account the antenna patterns, wave spreading, earth curvature, ground conductivity, path lengths, and antenna patterns including ground image effects.

The reflection coefficient $||R||$ was obtained from analysis of the parallel skywave components and is plotted as a function of frequency in part C of Figures 3 through 19. The $||R||$ coefficient for 16 kHz is plotted as a function of time-of-day in part F along with the average of the indicated week for reference purposes. From the perpendicular skywave pulse, the coefficient $||R_{\perp}||$ was obtained and appears

3. Wait, J. R., and Howe, H. H. (1956) Amplitude and Phase Curves for Ground-Wave Propagation in the Band 200 Cycles per Second to 500 Kilocycles, Nat. Bur. Stand. U.S. Circ. No. 574.
4. Budden, K. G. (1961) Radio Waves in the Ionosphere, p. 85, Cambridge University Press, London.

as a function of frequency in part D. The 16 kHz $\|R\|$ is shown along with its reference in part J. Parts H and L present the average, by time block, of the daily $\|R\|$ and $\|R\|$ data presented in parts F and J, respectively.

For certain coefficient data points, plotted as asterisks (*), the reflection coefficient appears without a corresponding GMH. For these particular data, only the skywave-groundwave ratios could be obtained as the skywaves were too weak to provide reliable group delay information. The reflection coefficients were therefore estimated using a nominal GMH of 80 km in the calculations. These estimated coefficient values are included in the averages presented in parts H and L, but the assumed heights are not used in the GMH averages shown in parts G and K.

5. SUPPLEMENTARY INFORMATION

For purposes of comparison and interpretation, certain supplementary data are presented. Part M of the figures shows the magnitude of the horizontal component of the polar magnetic field as recorded on a three axis fluxgate magnetometer and part N presents 30-MHz riometer data, an indicator of D-region particle precipitation. These supplementary data were recorded at 30-sec intervals by RADC/EEP at Thule AB; the curves represent the average of 10-minute periods. The solar zenith angle is given in part O of Figures 3 through 19 for the indicated mid-week date.

6. IONOSPHERIC DISTURBANCE DATA

During the period covered by this report the effects of ionospheric disturbances are seen on several occasions in both the ionosounder and the supplementary data. A moderate PCA disturbance occurred beginning on 19 Sept (Day 262). The riometer data indicated a maximum absorption of about 4 dB on the 19th followed by a recovery over the next several days. A second event was recorded on 24 Sept (Day 267), this disturbance produced about 2 dB absorption and lasted 5 days. A third PCA event occurred on 22 Nov (Day 326); this was a minor disturbance producing only 0.75 dB absorption. The VLF/LF ionosounder records show decreases in group heights and reflection coefficients coincident with these disturbances.

The ionosounder data show several other occasions when disturbances occurred which are not seen in the riometer data. These events can be easily seen as lowered group reflection heights during the period 9 - 18 Sept (Days 252 - 261) and on 6 Oct (Day 279) and 13 Oct (Day 286). It is probable that these disturbances resulted from very small particle fluxes below the level to which the riometer is sensitive.

It appears that the VLF/LF ionosounder's response is very sensitive to a small particle flux.

7. ADDITIONAL COMMENTS

Intermittent operation of the transmitter during the period from DAY 250 through DAY 262 is responsible for the missing waveforms and degraded signal-to-noise ratio apparent in the three-dimensional displays. The added noise in the parallel channel during the period from DAY 297 through DAY 337 was caused by a receiver malfunction.

This report is one of a series.^{5, 6, 7, 8, 9, 10, 11, 12, 13} Comments and suggestions for improving its usefulness should be addressed to the Propagation Branch (EEP), Electromagnetic Sciences Division, Deputy for Electronic Technology (RADC/EEP), Hanscom AFB, Massachusetts 01731.

(Because of the large number of references cited above, they will not be listed here. See Reference Page 13 for References 5 through 13.)

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1. Lewis, E. A., Rasmussen, J. E., and Kossey, P. A. (1973) Measurements of ionospheric reflectivity from 6 to 35 kHz, *J. Geophys. Res.* 78:19.
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12. Rasmussen, J. E., Turtle, J. P., Pagliarulo, R. P., and Klemetti, W. I. (1977) VLF/LF Reflectivity of the Polar Ionosphere, 2 January - 30 April 1977, RADC-TR-77-251.
13. Rasmussen, J. E., Turtle, J. P., Pagliarulo, R. P., and Klemetti, W. I. (1978) VLF/LF Reflectivity of the Polar Ionosphere, 1 May - 3 September 1977, RADC-TR-77-428.

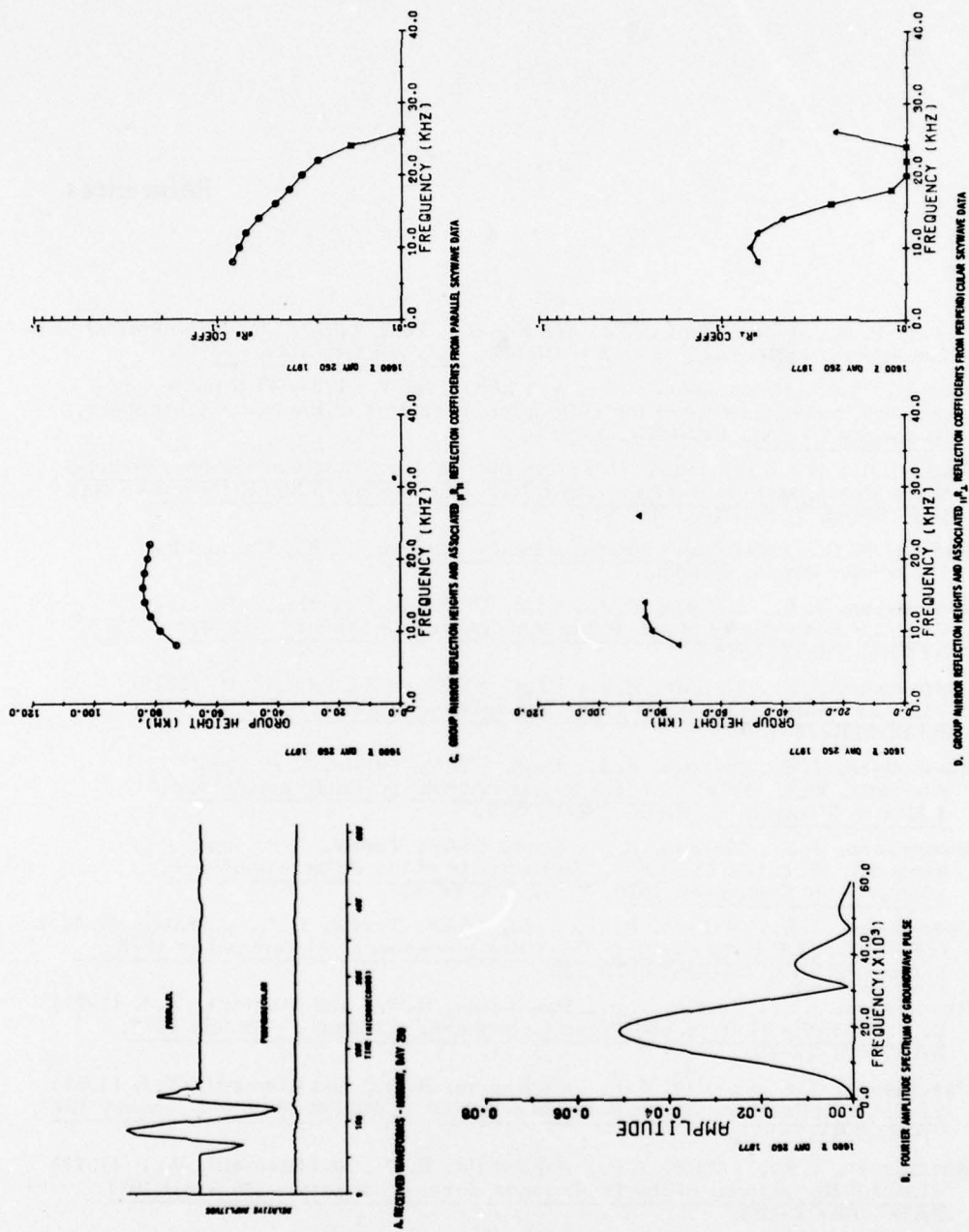


Figure 3. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 247 (4 Sep) - DAY 253 (10 Sep) 1977

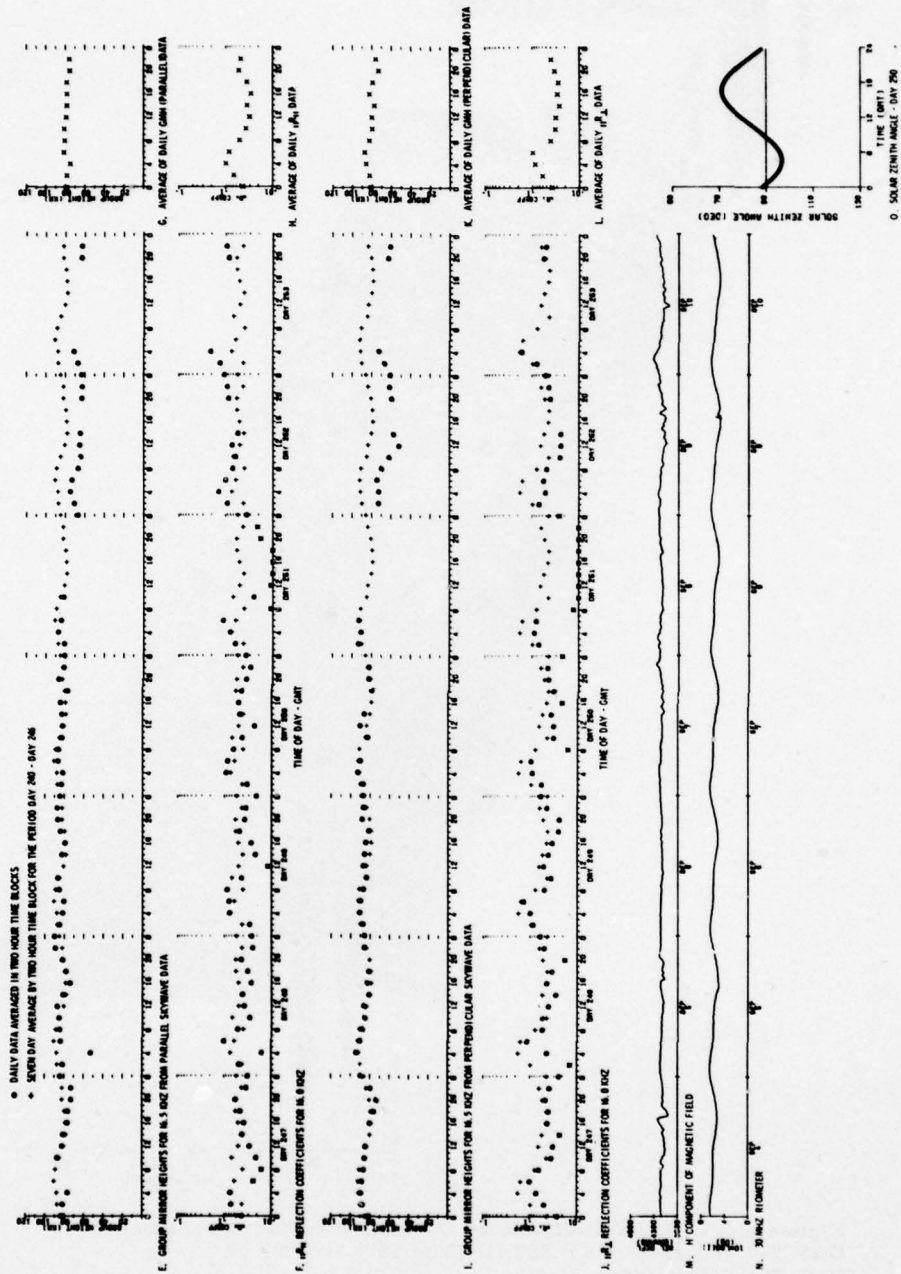


Figure 3. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 247 (4 Sep) - DAY 253 (10 Sep) 1977 (Cont)

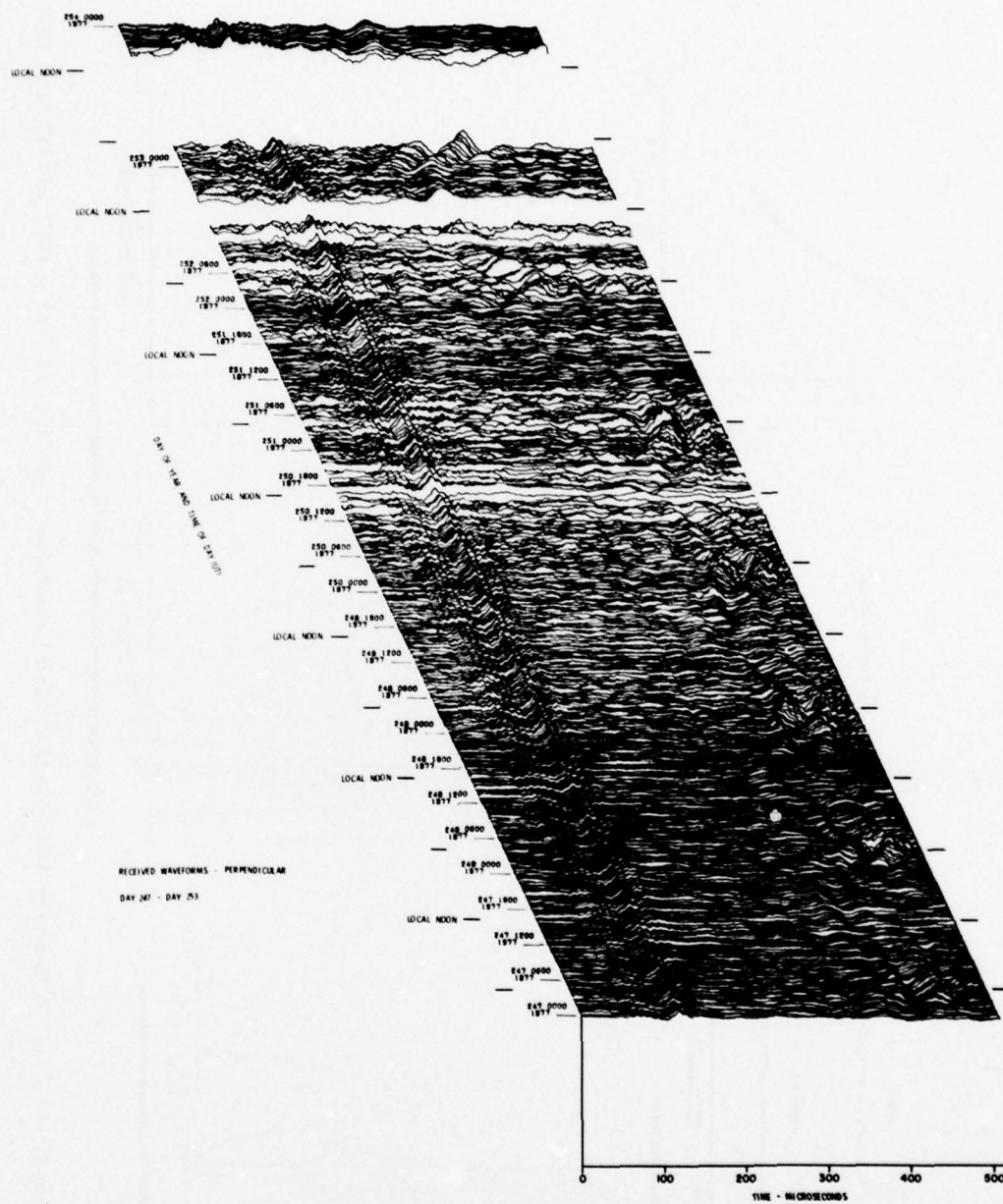


Figure 3. VLF/LF Reflectivity Data for the Polar Ionosphere,
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 Part S. \perp Waveform Display

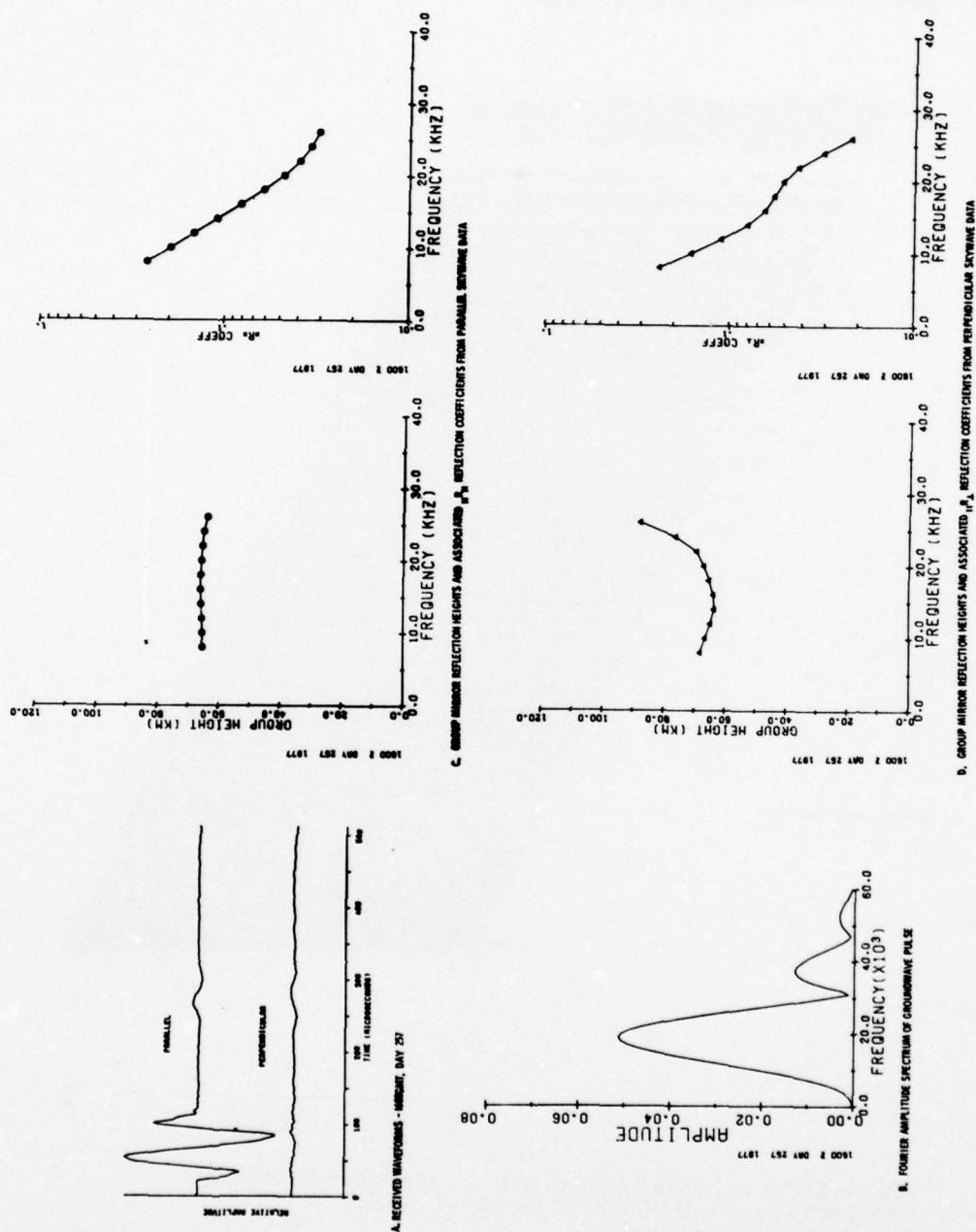


Figure 4. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 254 (11 Sep) - DAY 260 (17 Sep) 1977

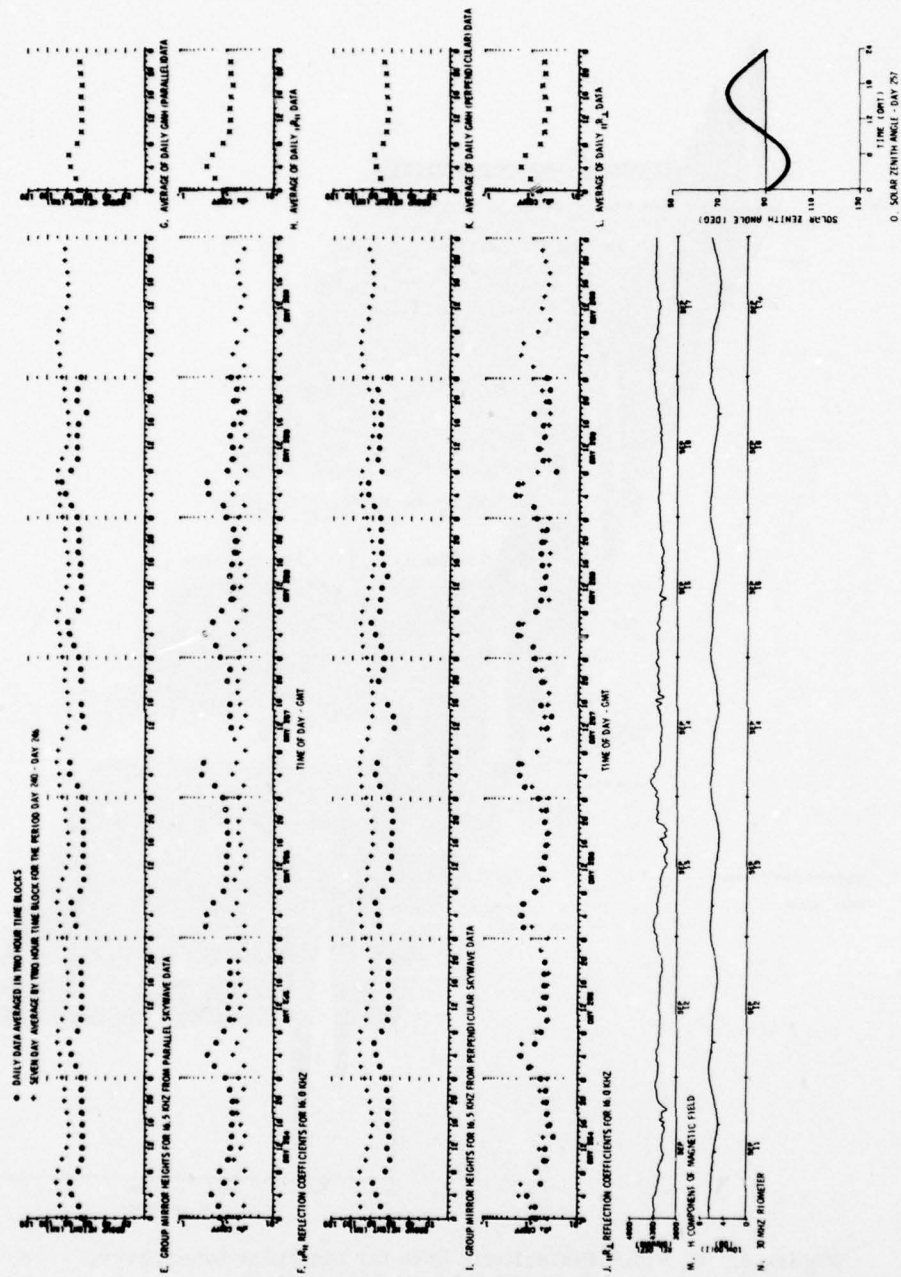


Figure 4. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 254 (11 Sep) - DAY 260 (17 Sep) 1977 (Cont)

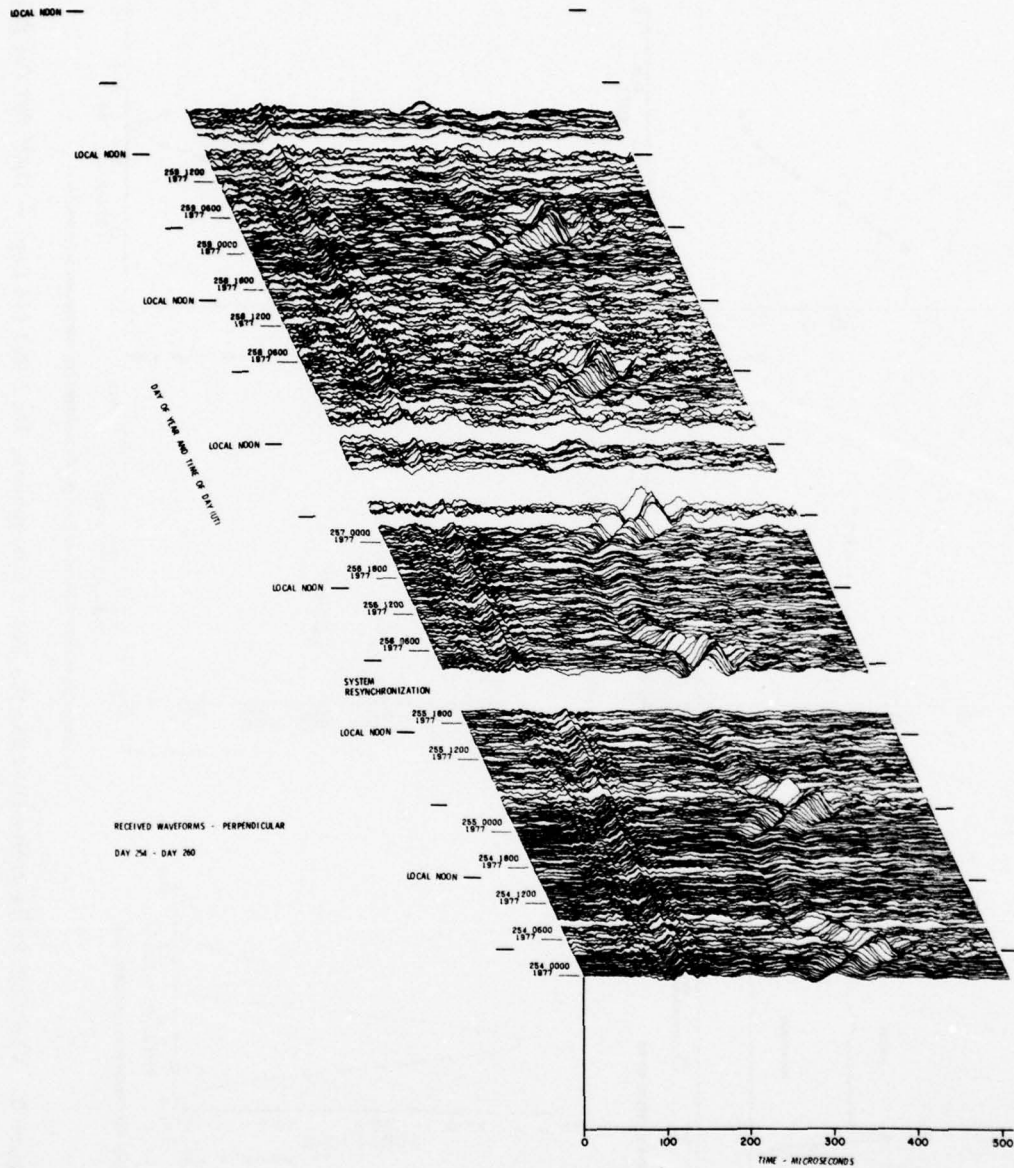


Figure 4. VLF/LF Reflectivity Data for the Polar Ionosphere,
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Part S. \perp Waveform Display

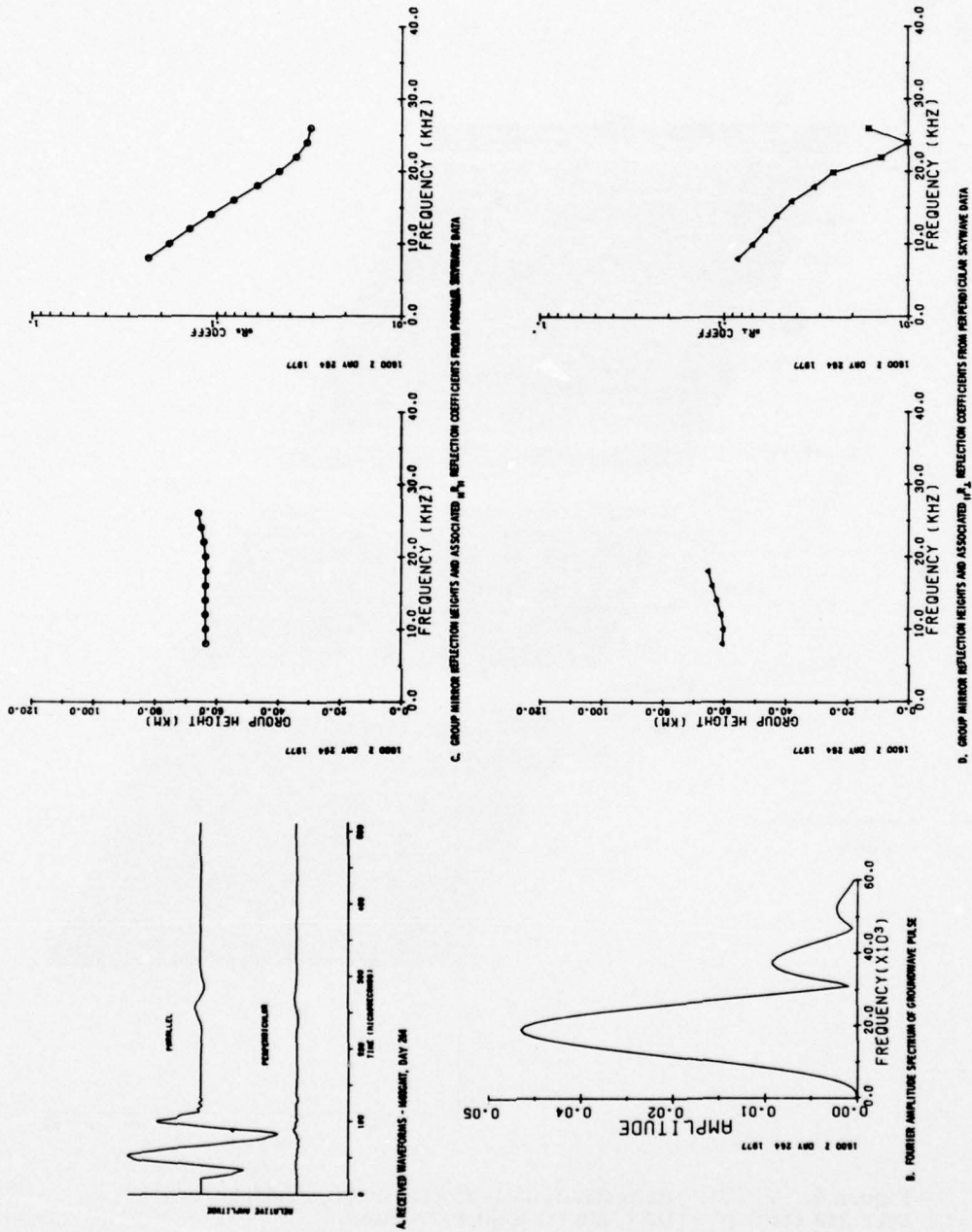


Figure 5. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 261 (18 Sep) - DAY 267 (24 Sep) 1977

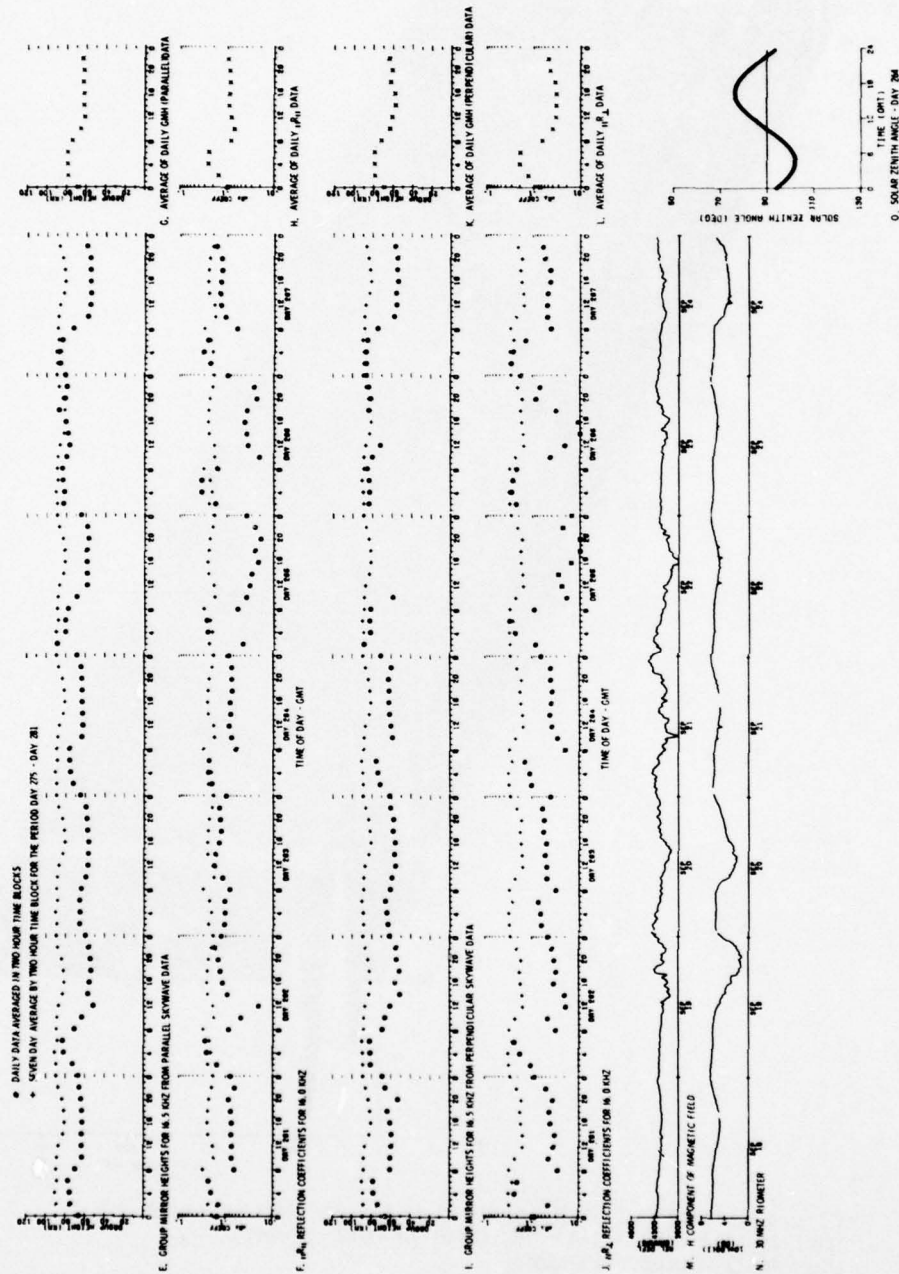


Figure 5. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 261 (18 Sep) - DAY 267 (24 Sep) 1977 (Cont)

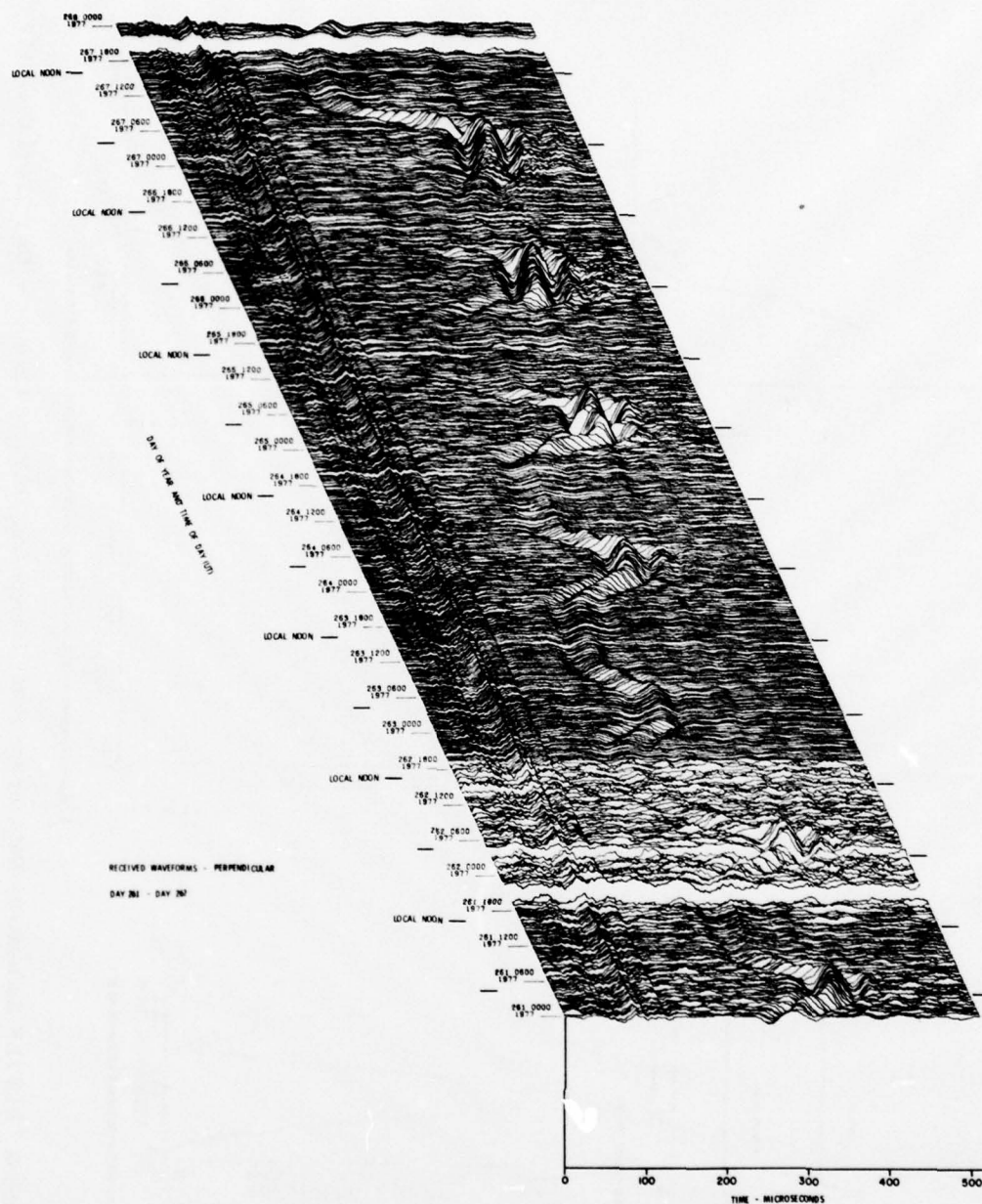


Figure 5. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 261 (18 Sep) - DAY 267 (24 Sep) 1977 (Cont)
 Part S. \perp Waveform Display

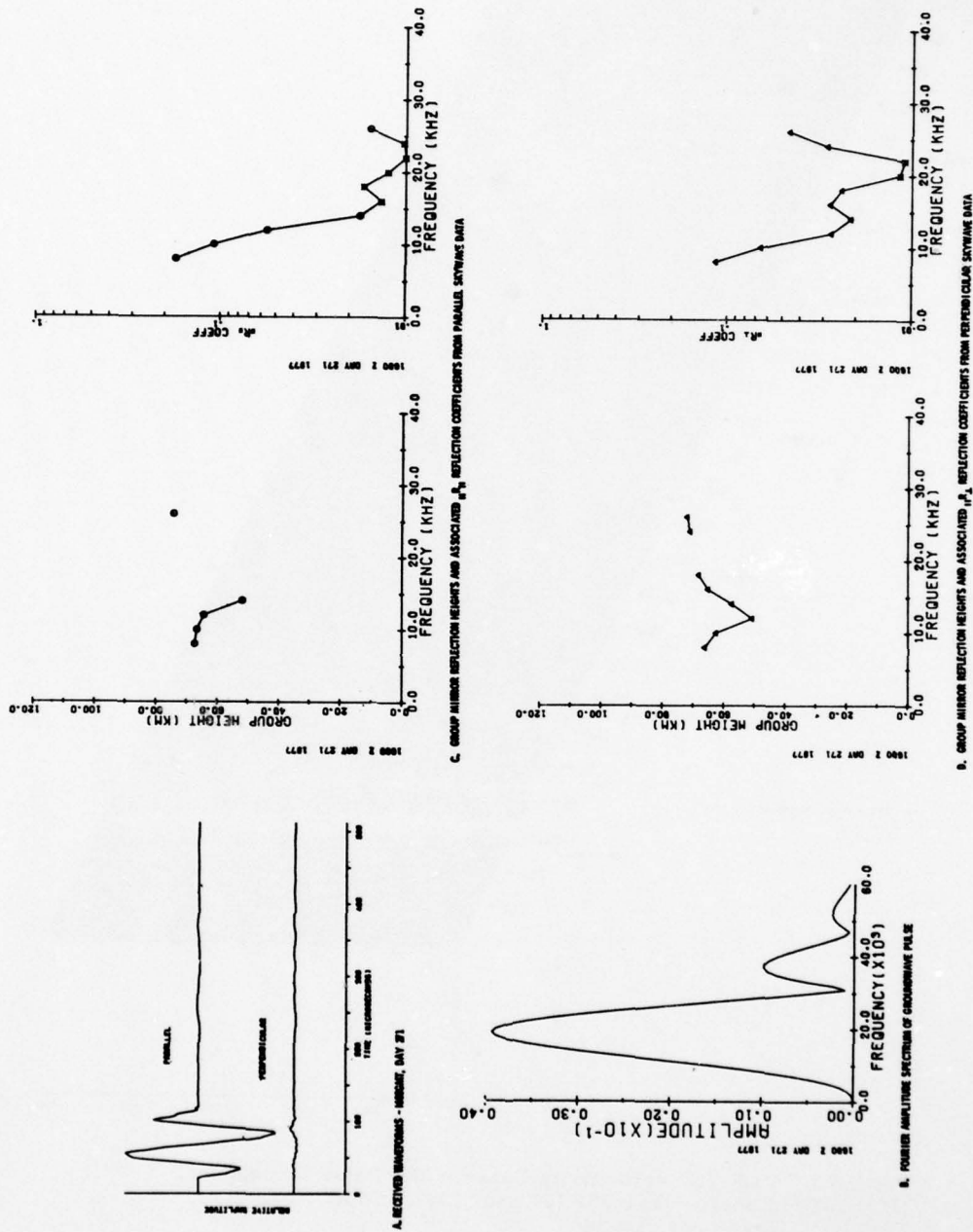


Figure 6. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 268 (25 Sep) - DAY 274 (1 Oct) 1977

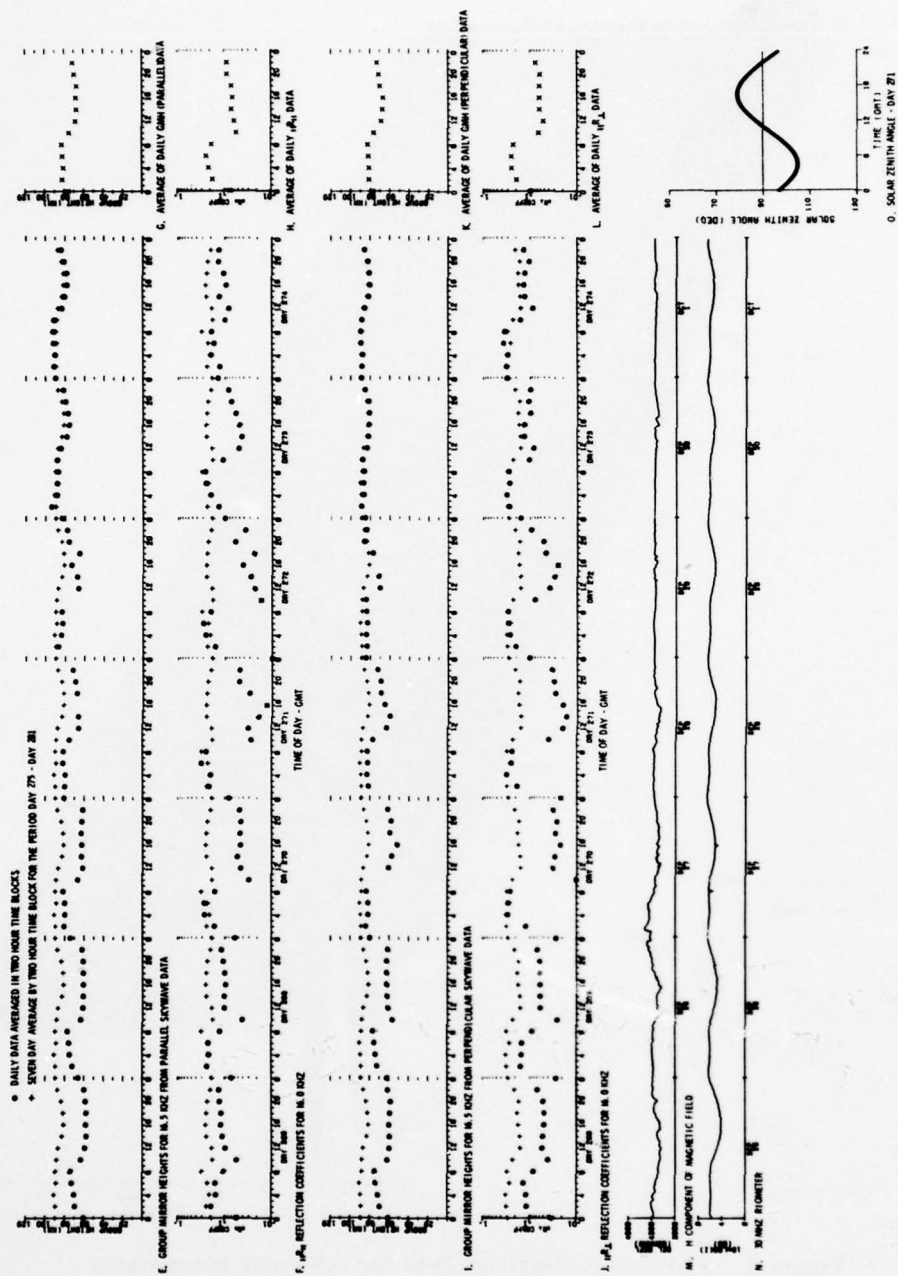


Figure 6. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 268 (25 Sep) - DAY 274 (1 Oct) 1977 (Cont)

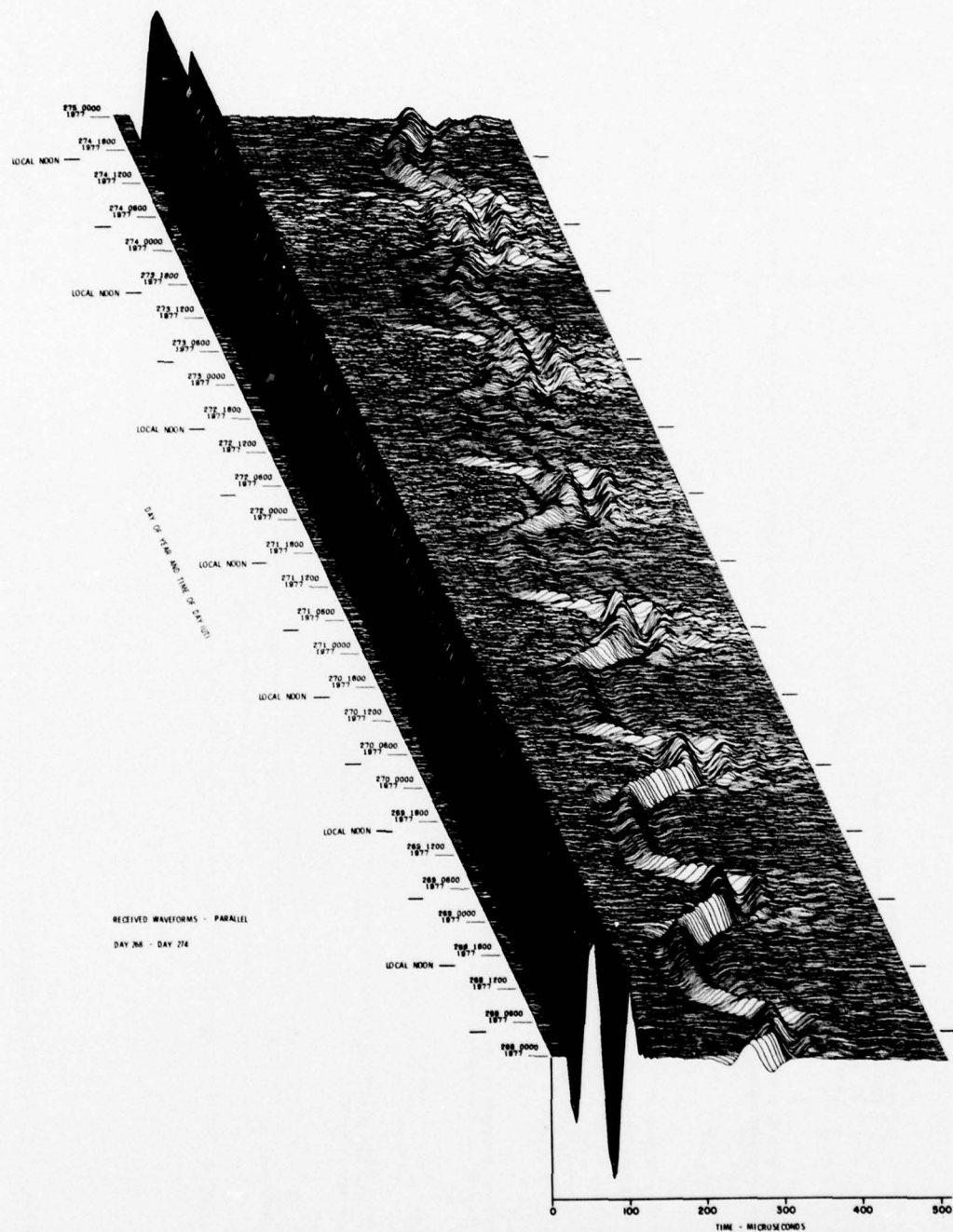


Figure 6. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 268 (25 Sep) - DAY 274 (1 Oct) 1977 (Cont)
 Part R. || Waveform Display

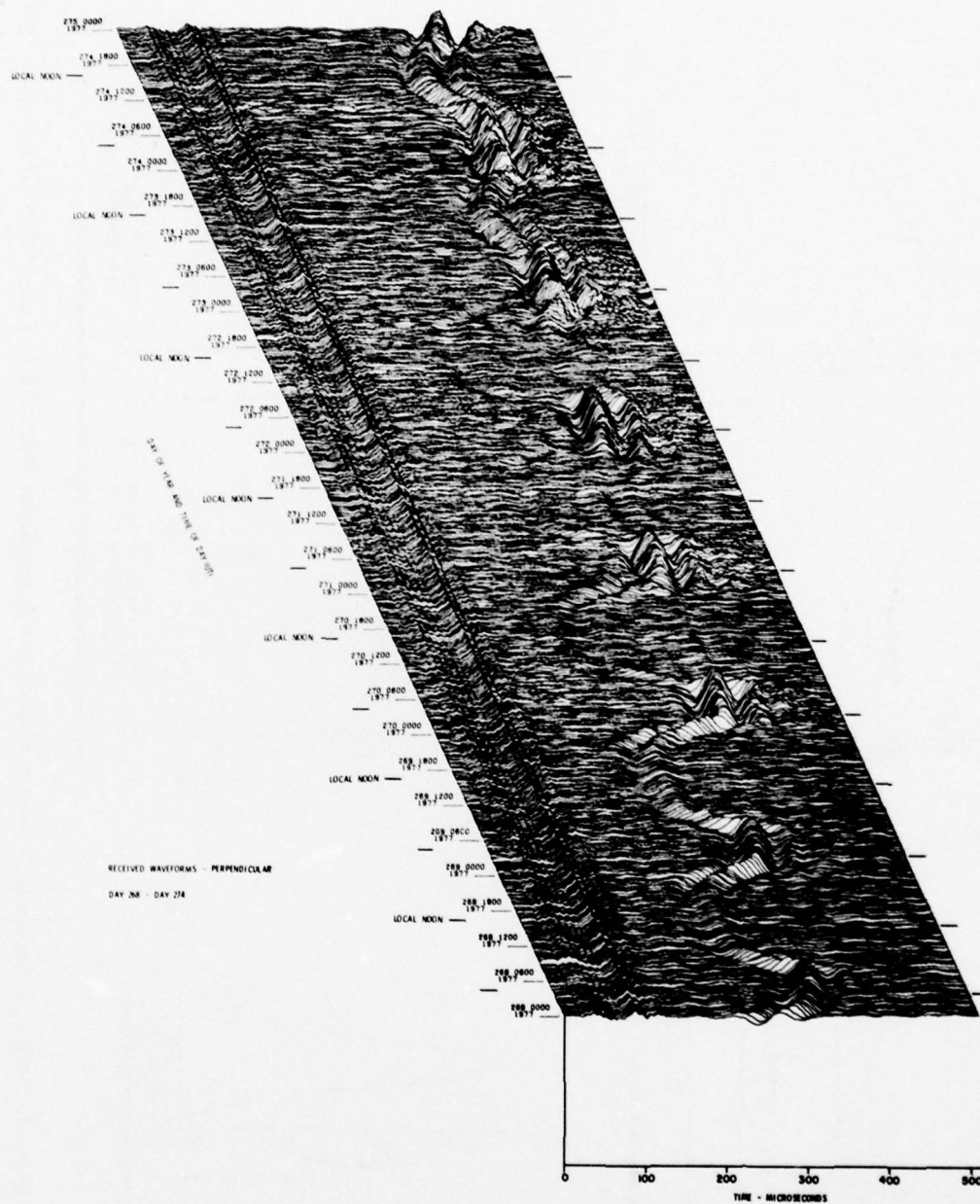


Figure 6. VLF/LF Reflectivity Data for the Polar Ionosphere,
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 Part S. \perp Waveform Display

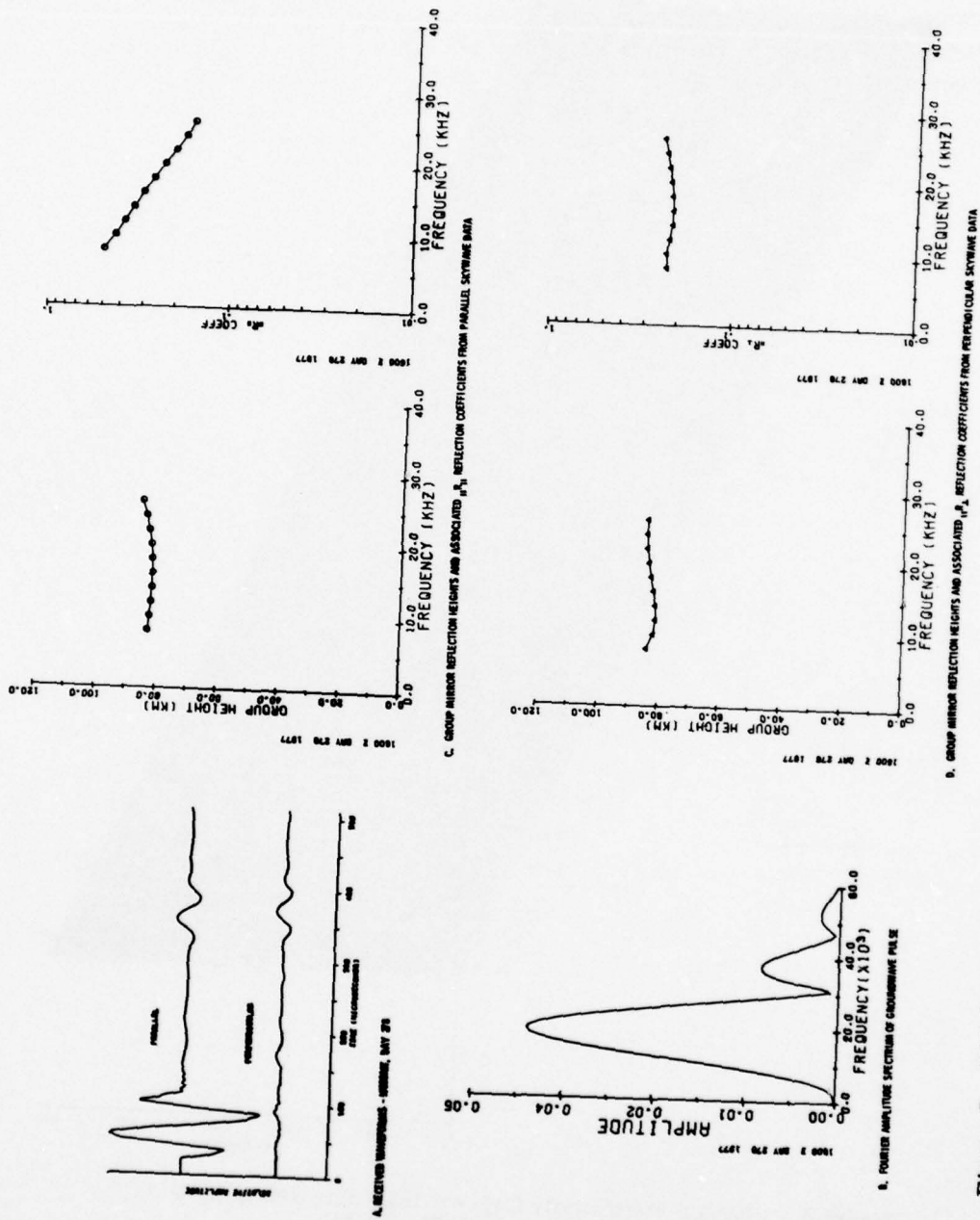


Figure 7. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 275 (2 Oct) - DAY 281 (8 Oct) 1977

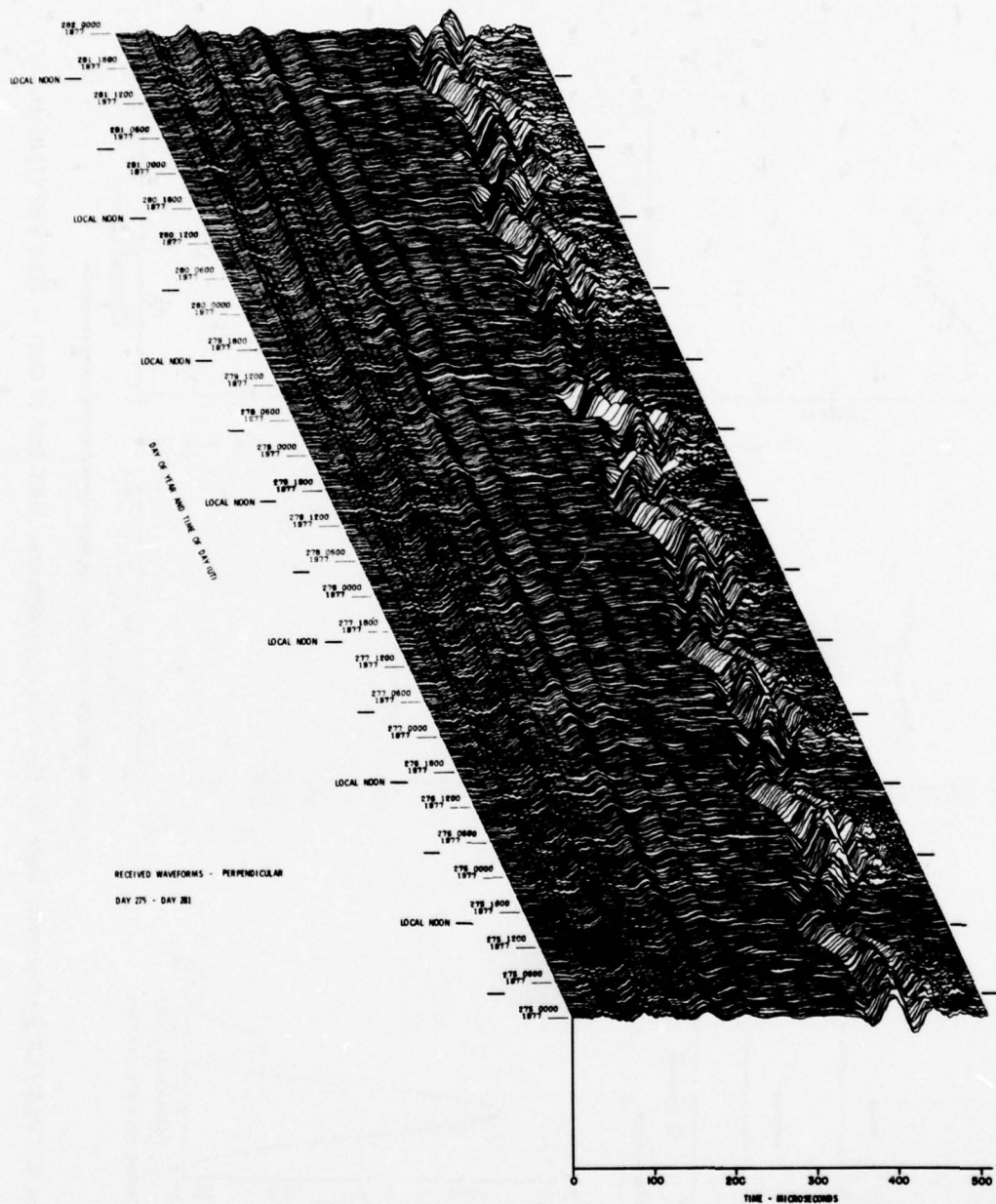


Figure 7. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 275 (2 Oct) - DAY 281 (8 Oct) 1977 (Cont)
 Part S. \perp Waveform Display

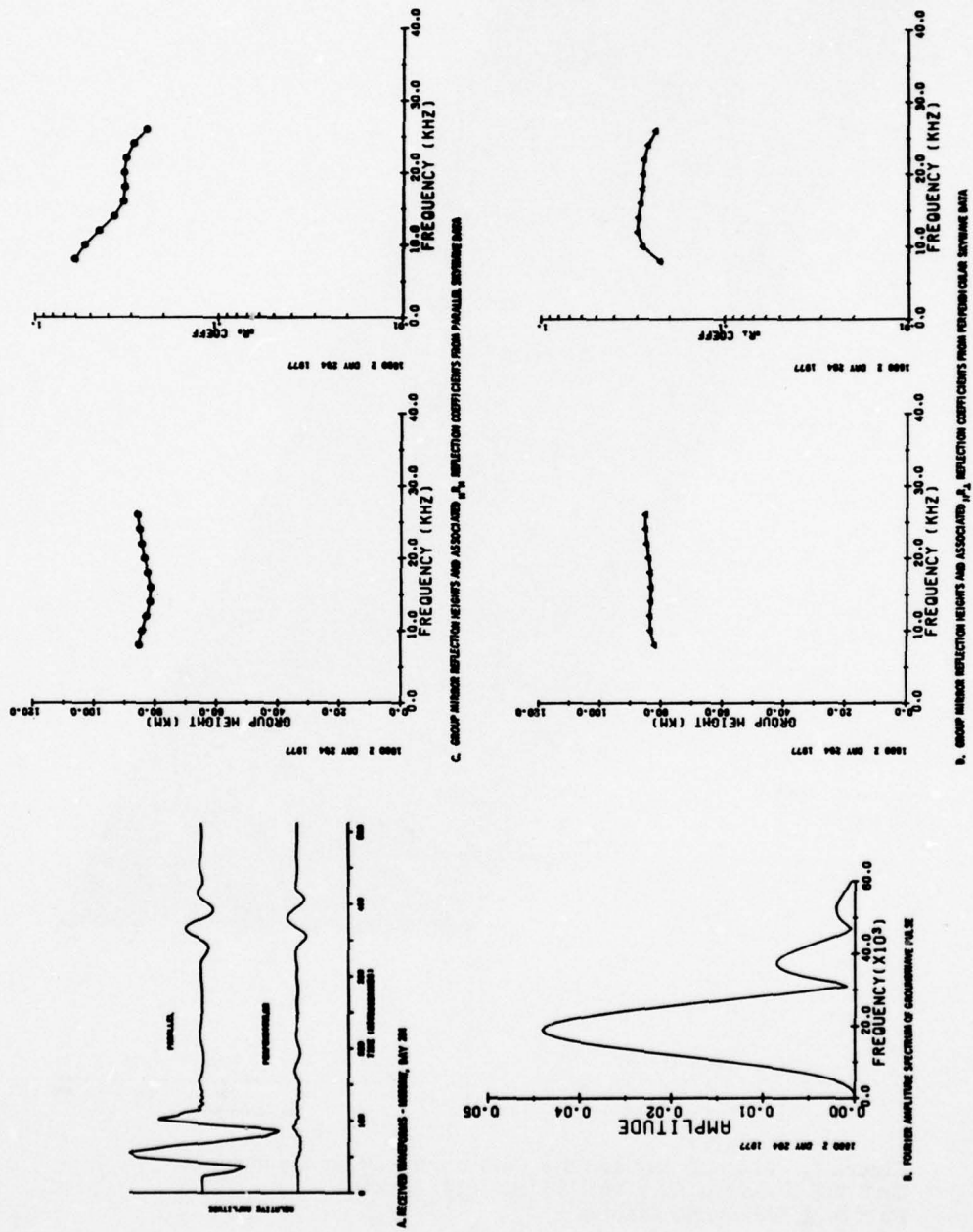


Figure 8. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 282 (9 Oct) - DAY 288 (15 Oct) 1977

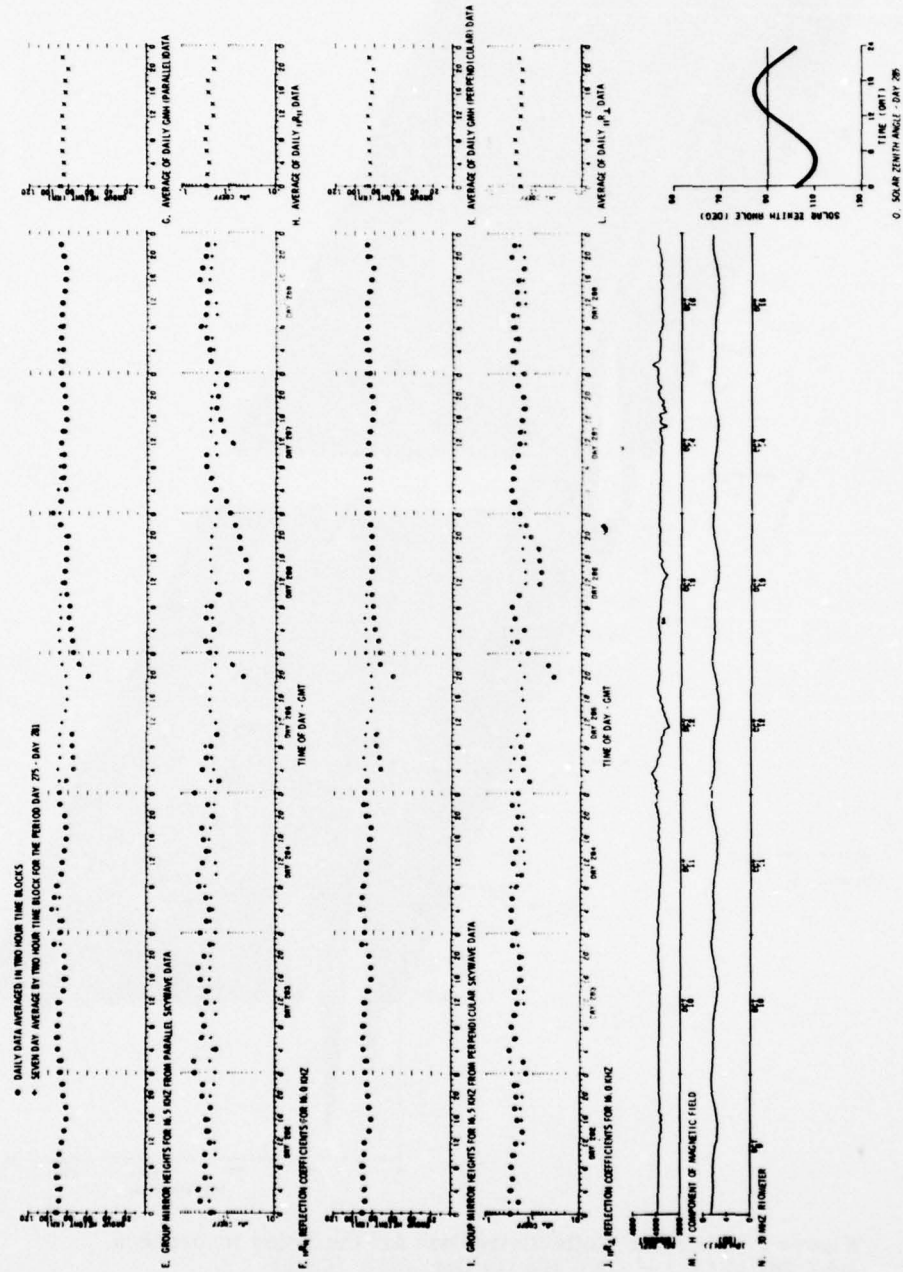


Figure 8. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 282 (9 Oct) - DAY 288 (15 Oct) 1977 (Cont)

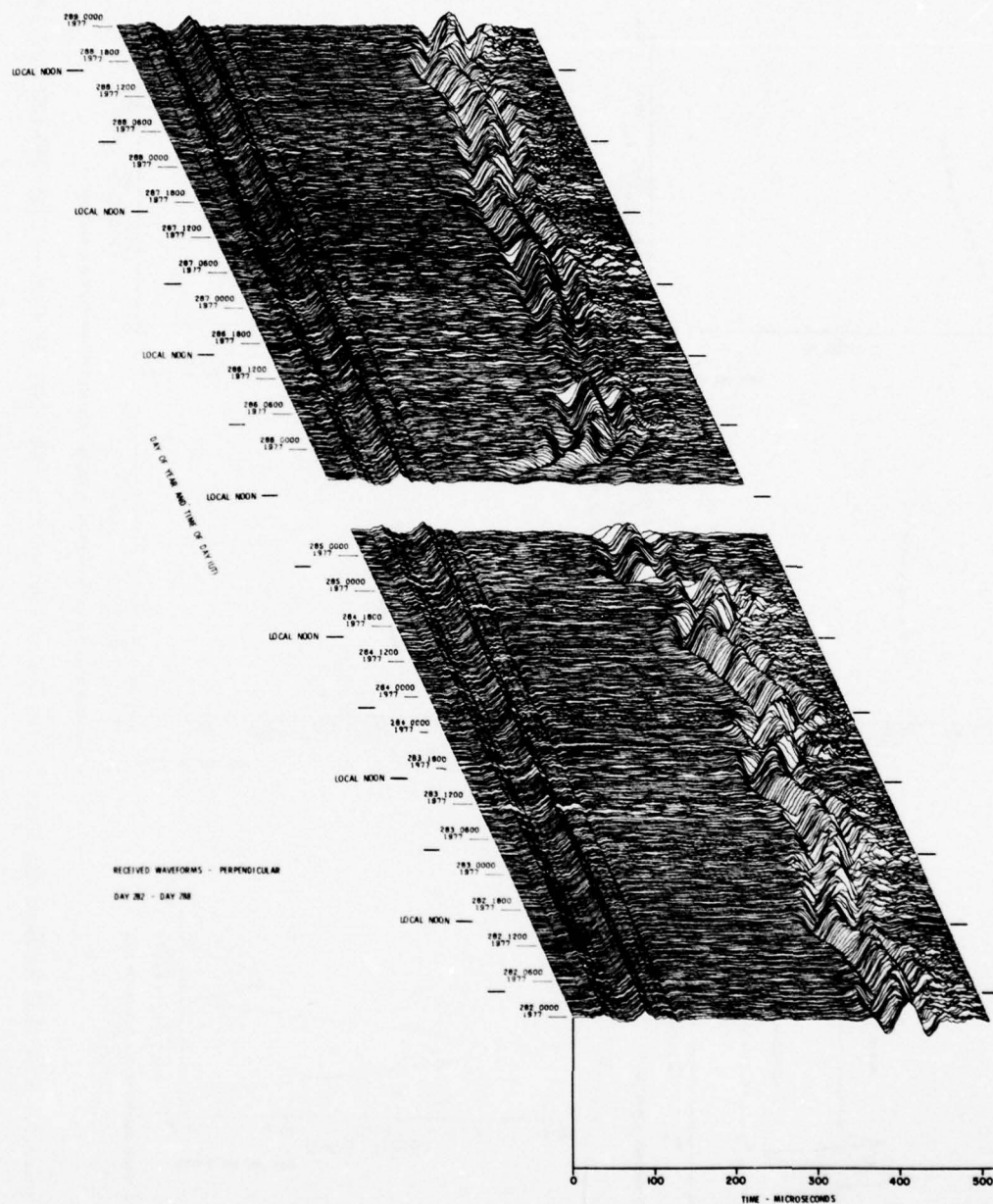


Figure 8. VLF/LF Reflectivity Data for the Polar Ionosphere,
DAY 282 (9 Oct) - DAY 288 (15 Oct) 1977 (Cont)
Part S. \perp Waveform Display

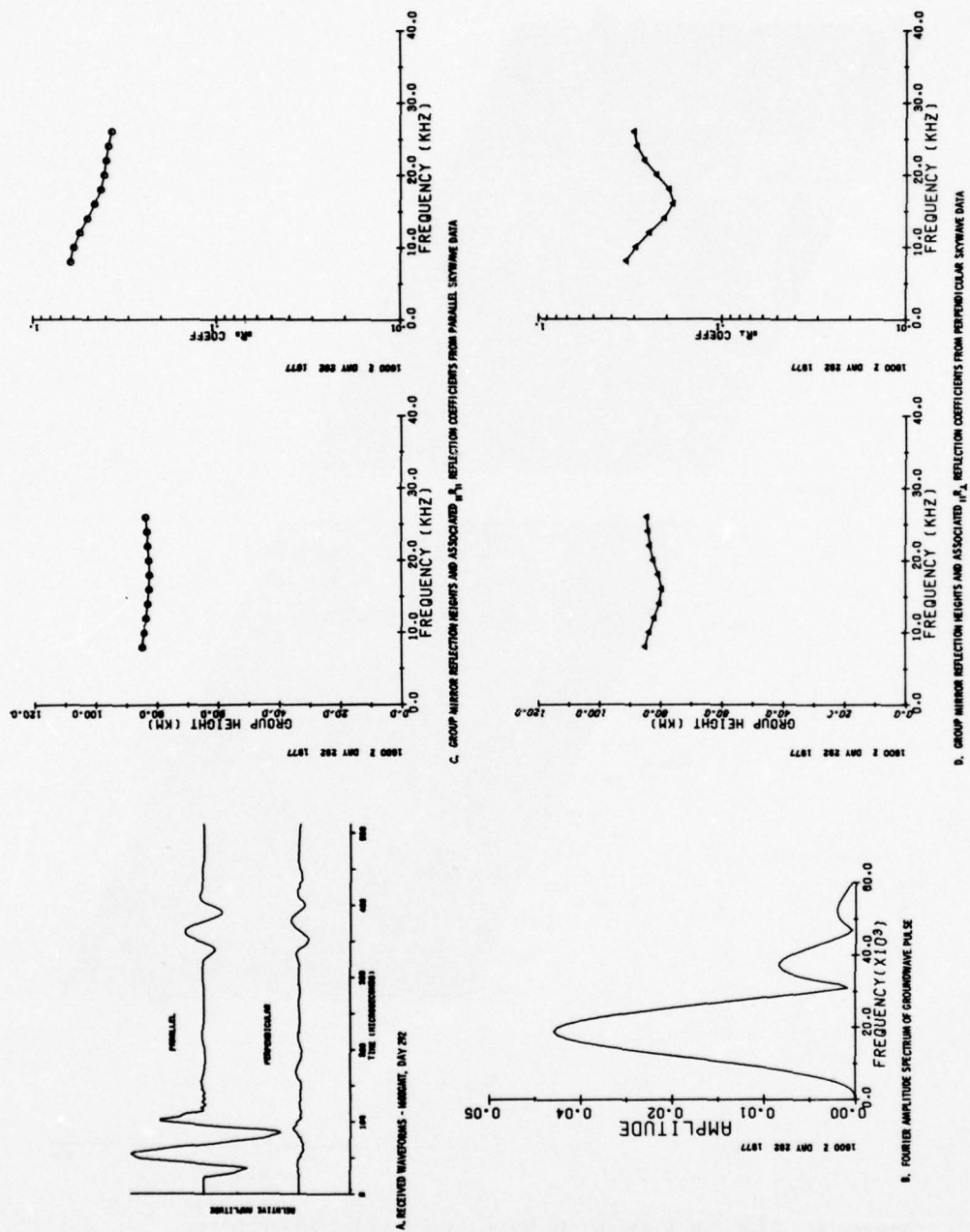


Figure 9. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 289 (16 Oct) - DAY 295 (22 Oct) 1977

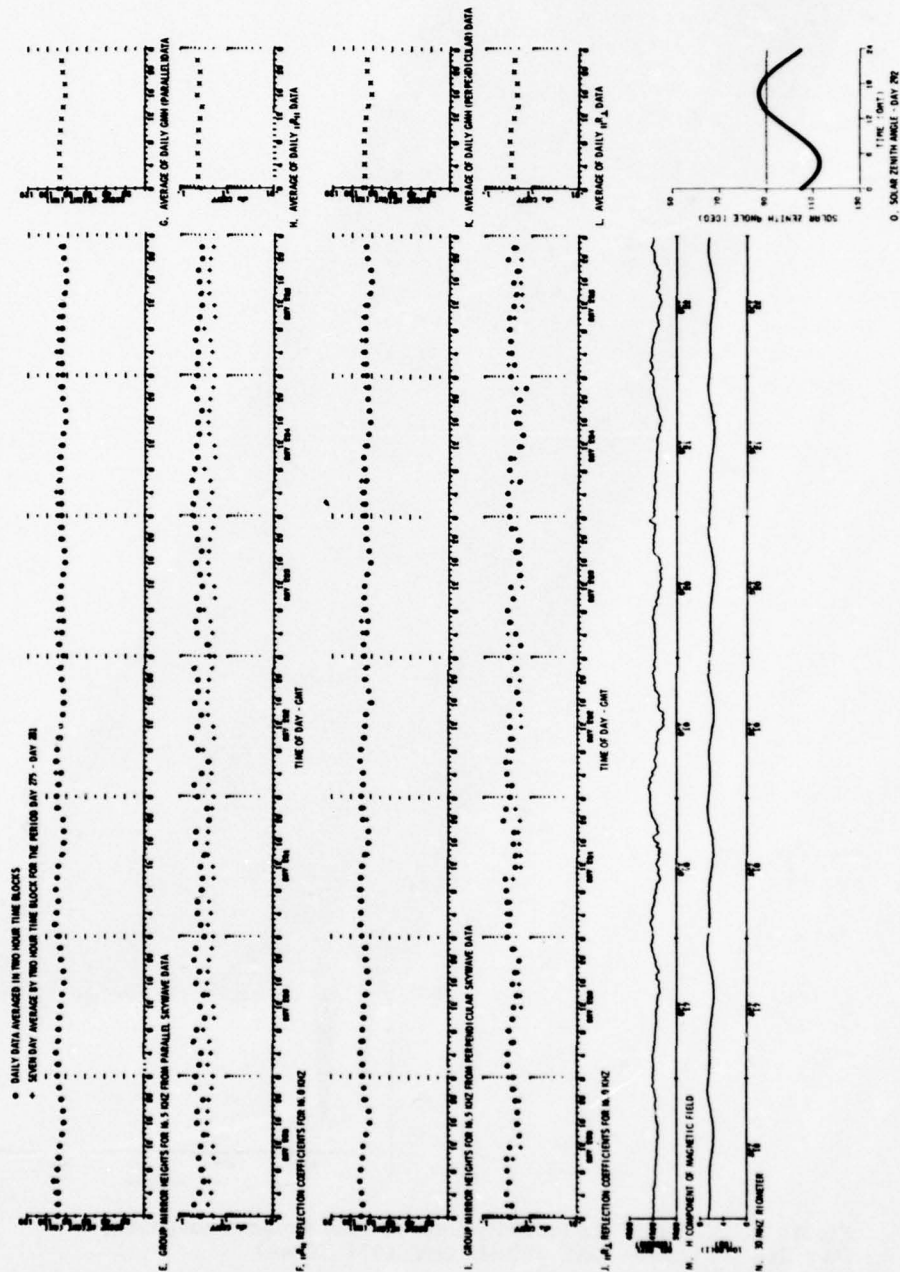


Figure 9. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 289 (16 Oct) - DAY 295 (22 Oct) 1977 (Cont)

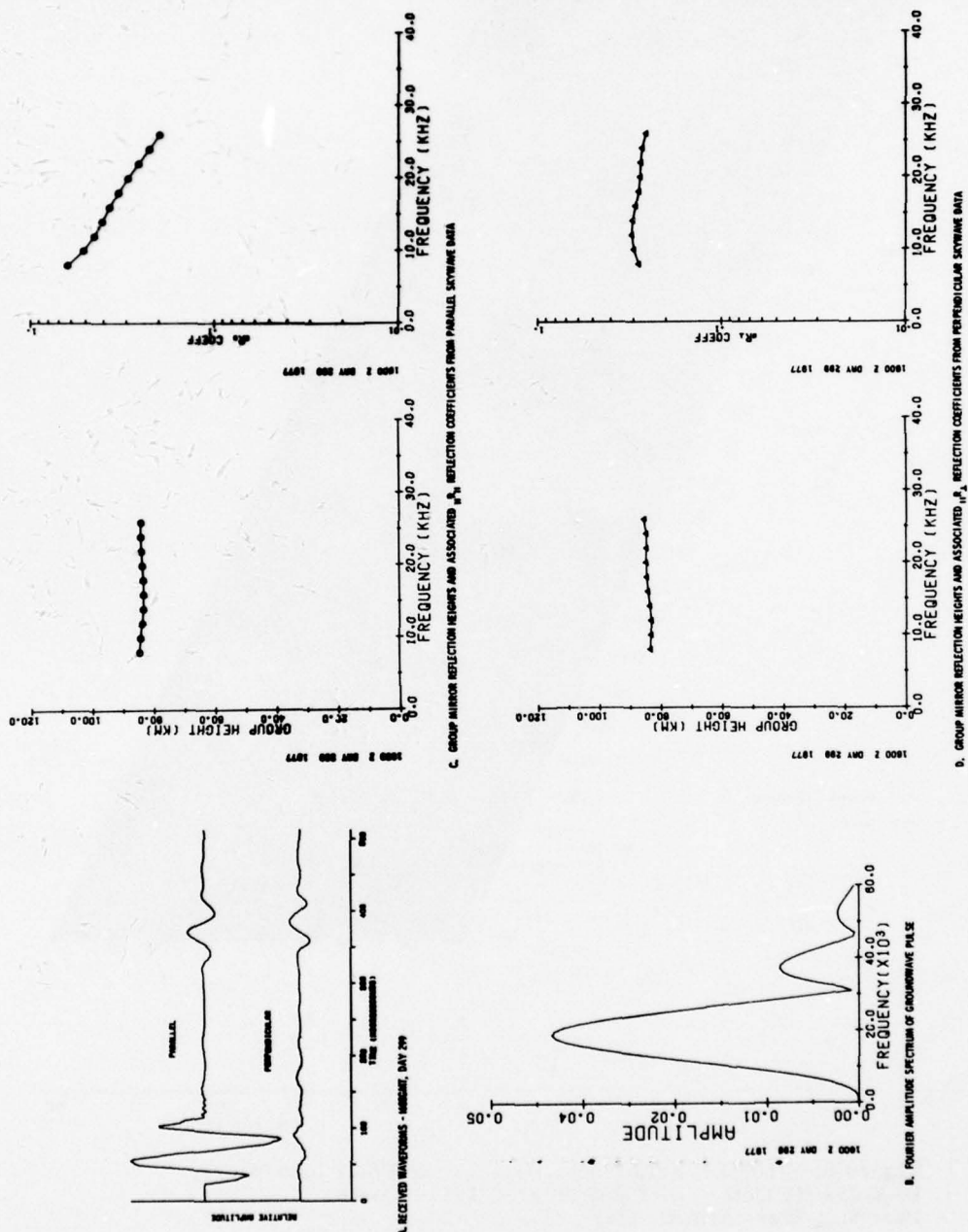


Figure 10. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 296 (23 Oct) - DAY 302 (29 Oct) 1977

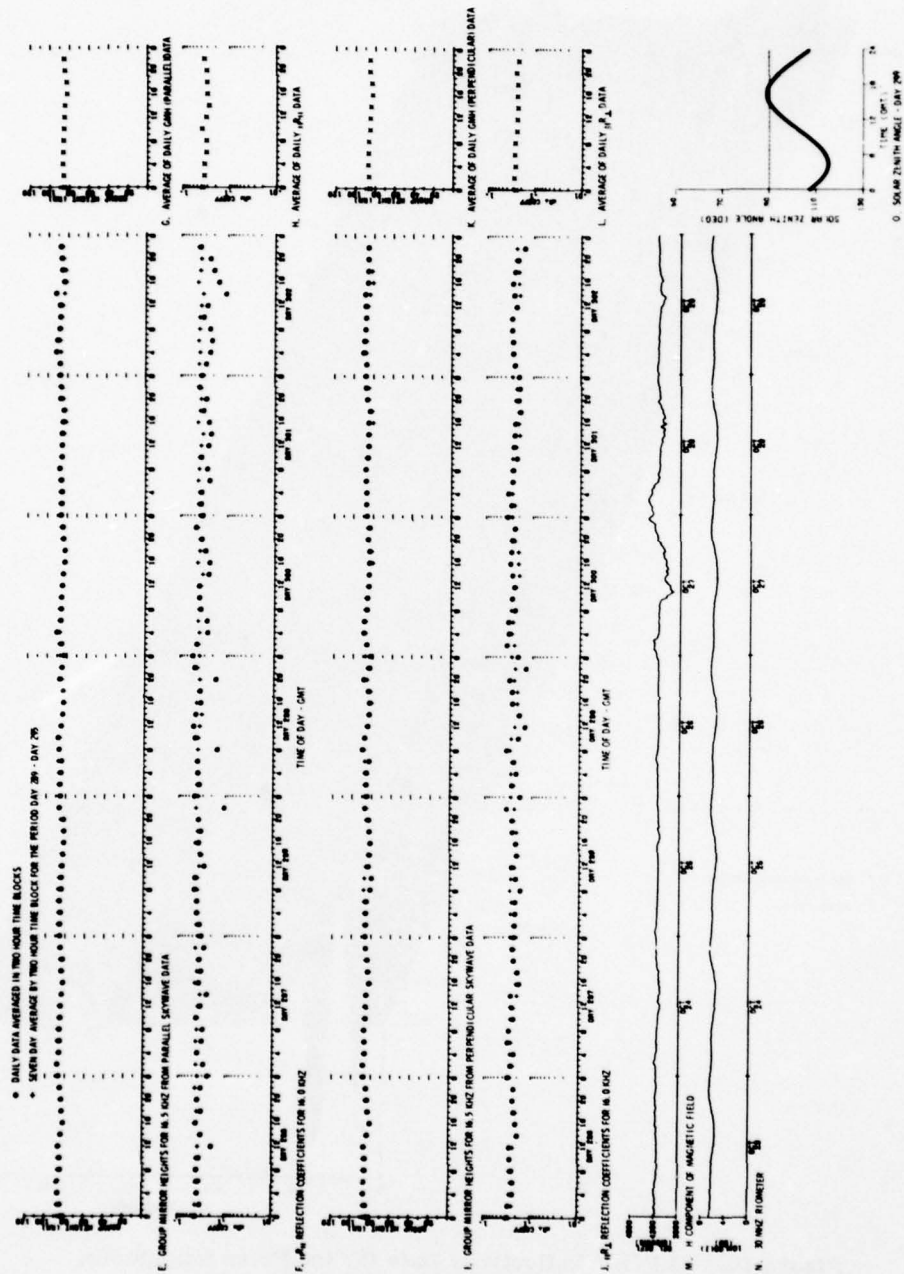


Figure 10. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 296 (23 Oct) - DAY 302 (29 Oct) 1977 (Cont)

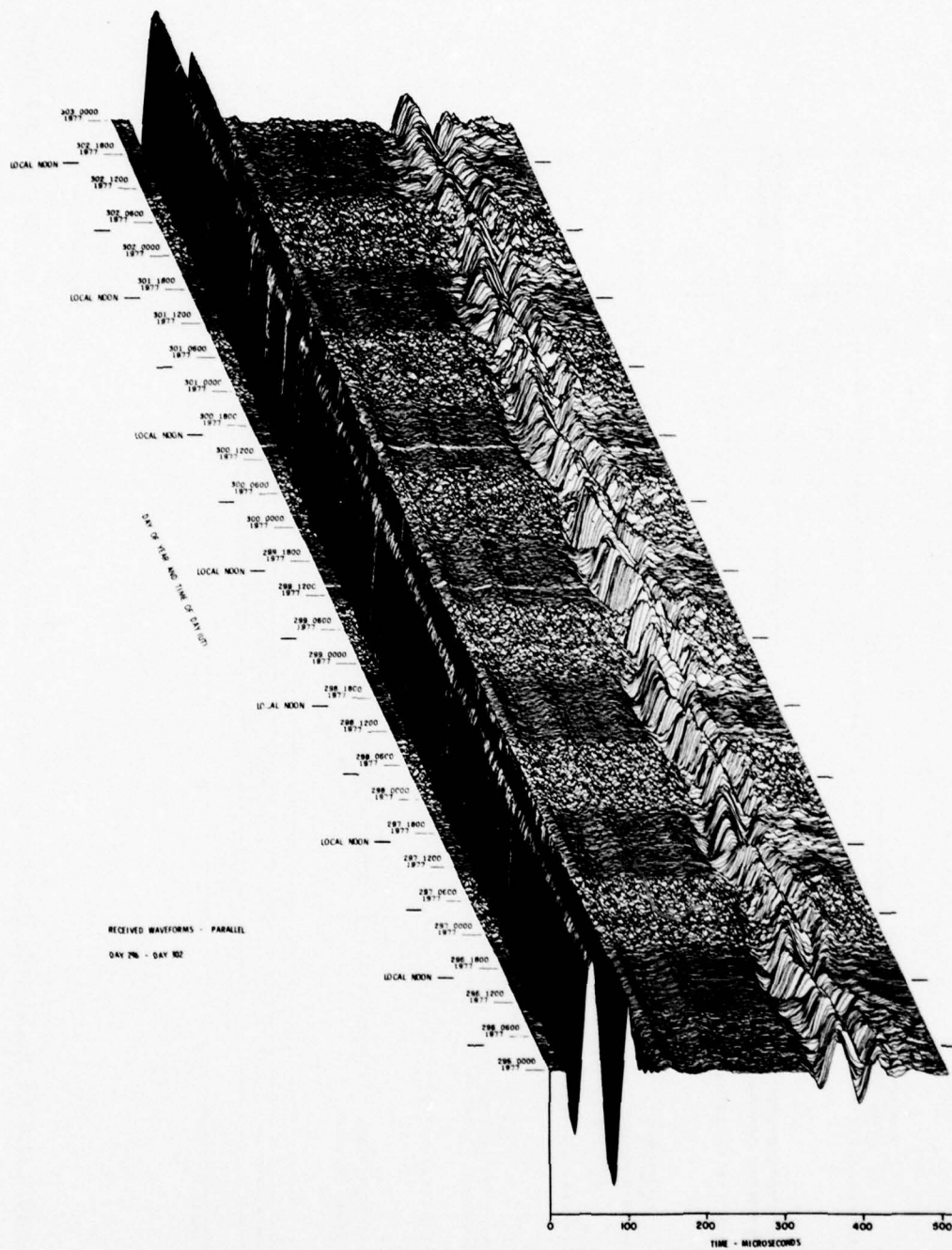


Figure 10. VLF/LF Reflectivity Data for the Polar Ionosphere,
DAY 296 (23 Oct) - DAY 302 (29 Oct) 1977 (Cont)
Part R. || Waveform Display

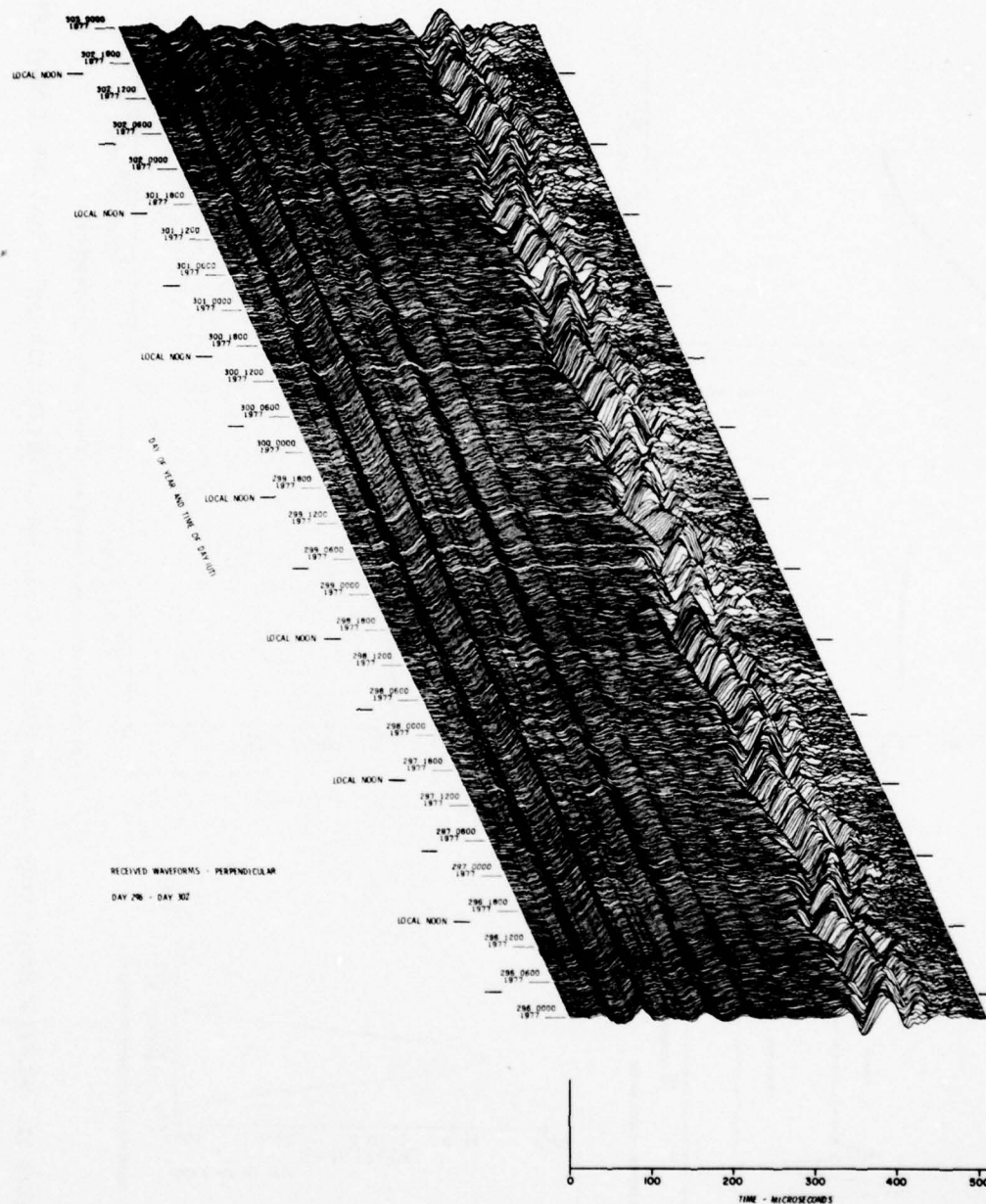


Figure 10. VLF/LF Reflectivity Data for the Polar Ionosphere,
DAY 296 (23 Oct) - DAY 302 (29 Oct) 1977 (Cont)
Part S. ⊥ Waveform Display

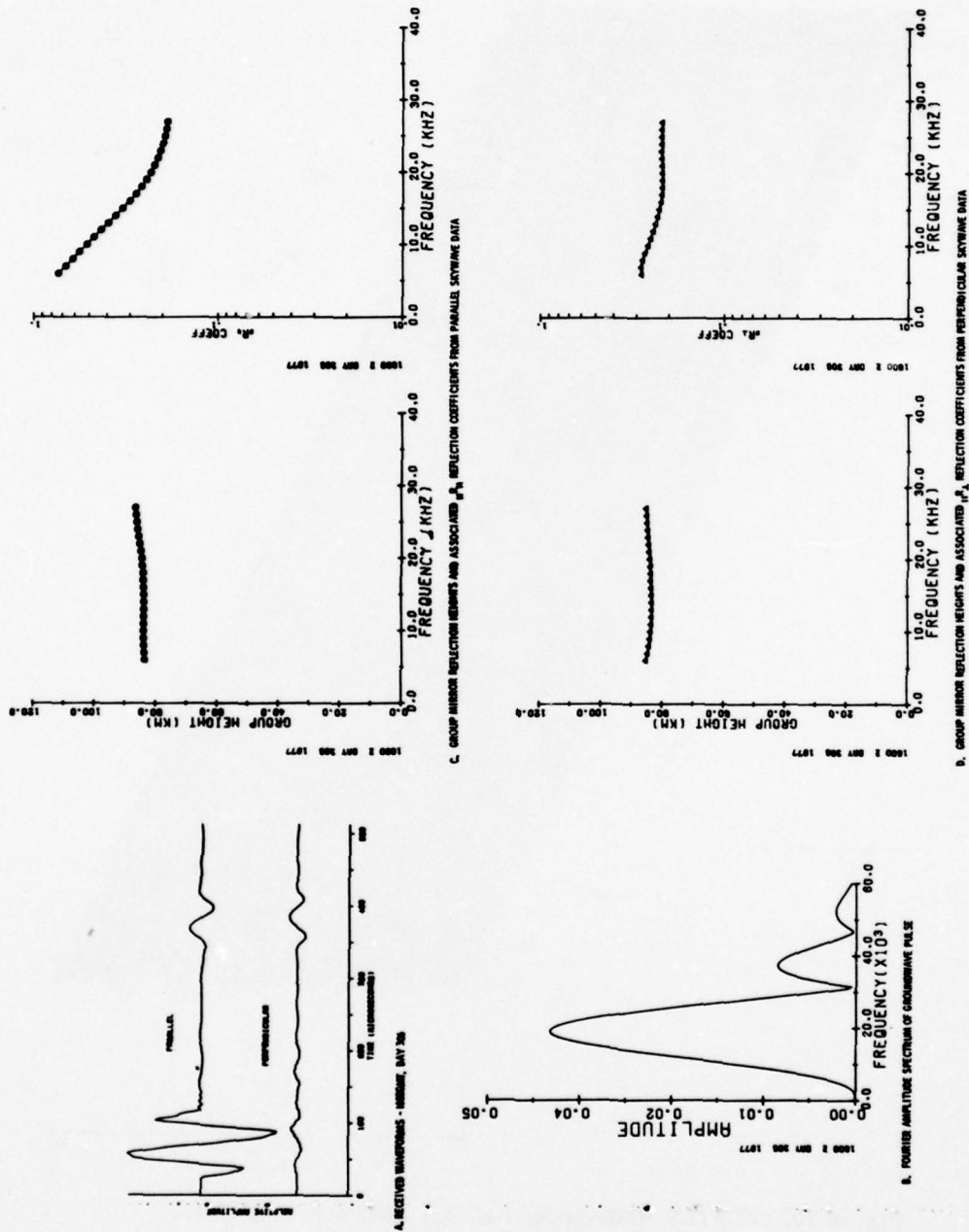


Figure 11. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 303 (30 Oct) — DAY 309 (5 Nov) 1977

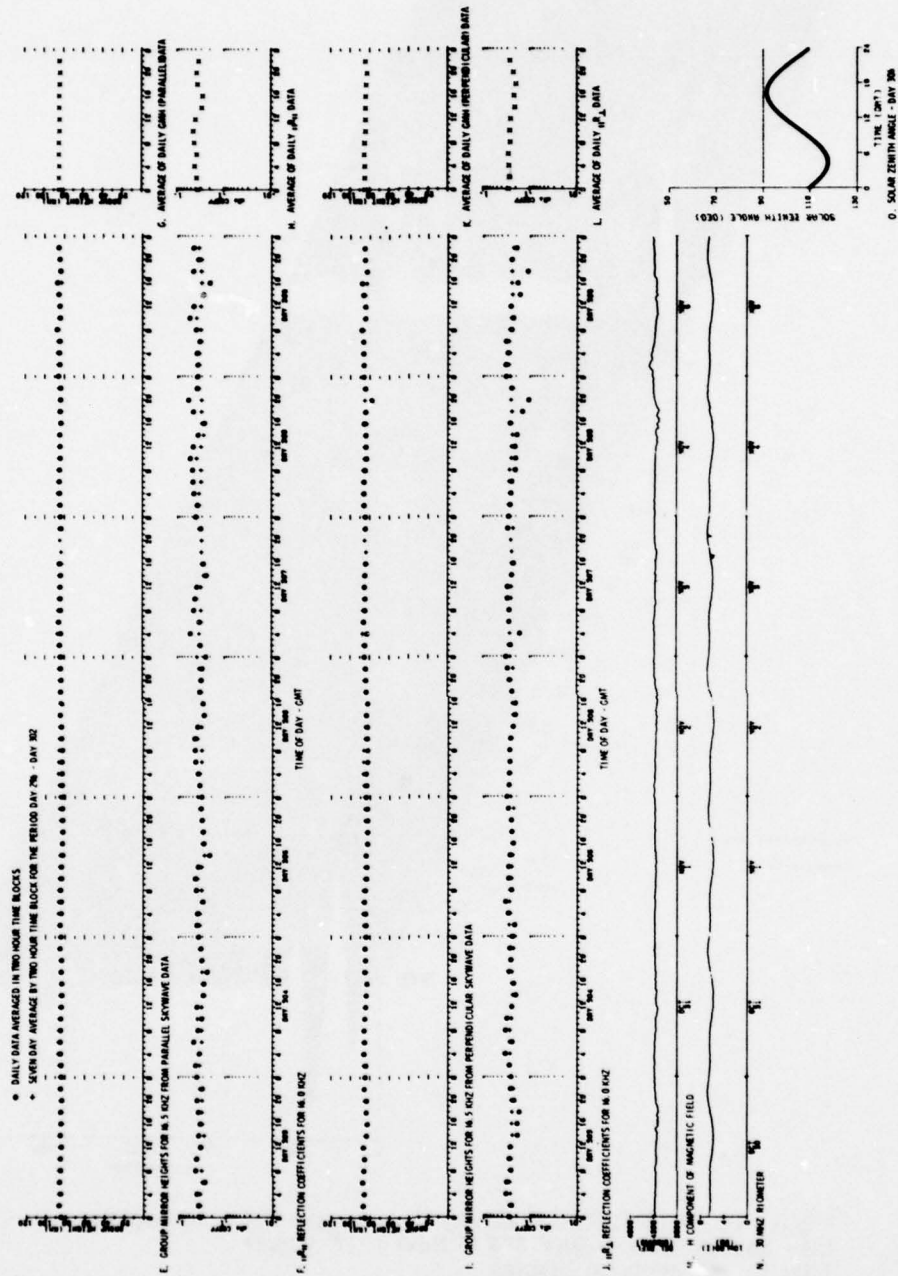


Figure 11. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 303 (30 Oct) - DAY 309 (5 Nov) 1977 (Cont)

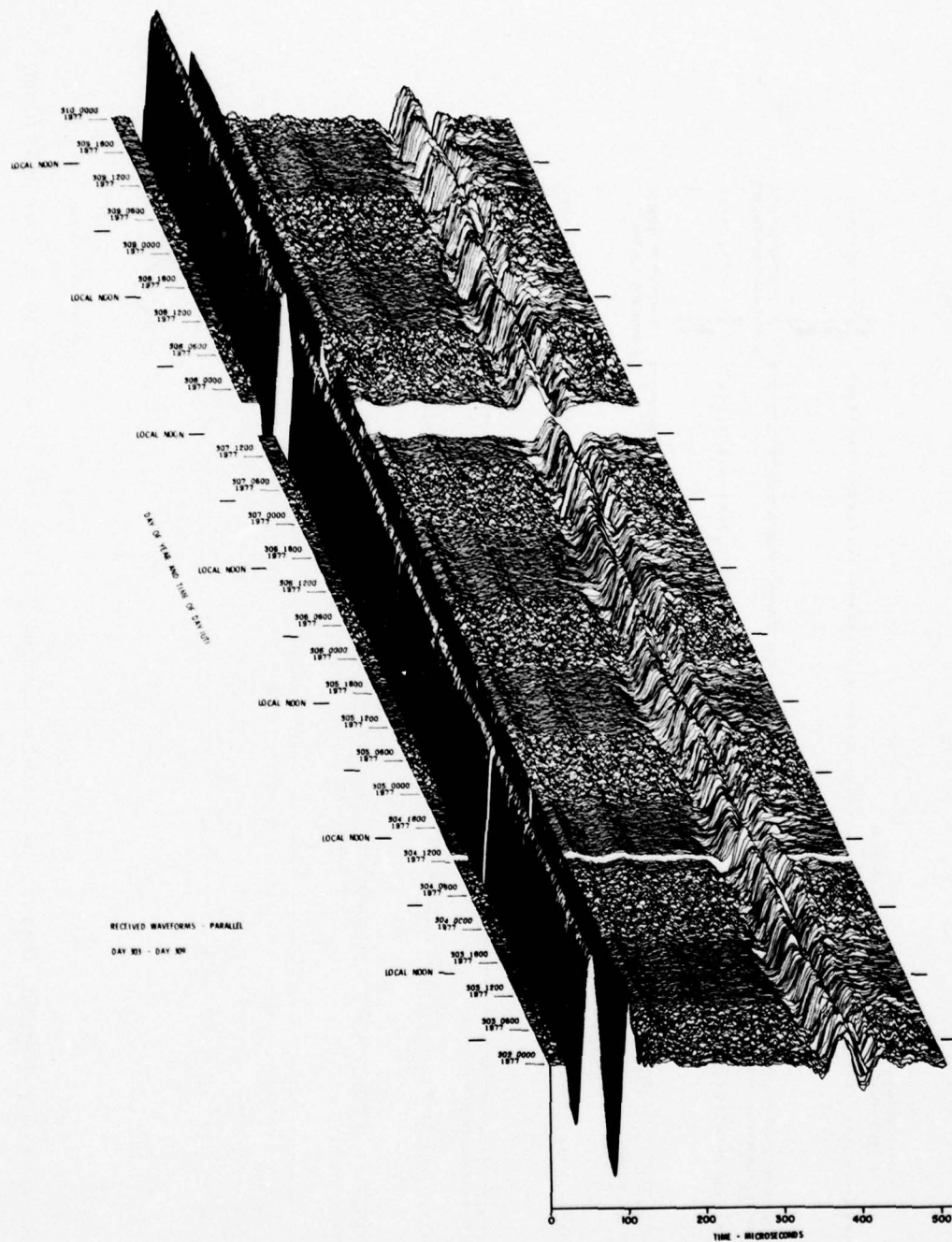


Figure 11. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 303 (30 Oct) - DAY 309 (5 Nov) 1977 (Cont)
 Part R. || Waveform Display

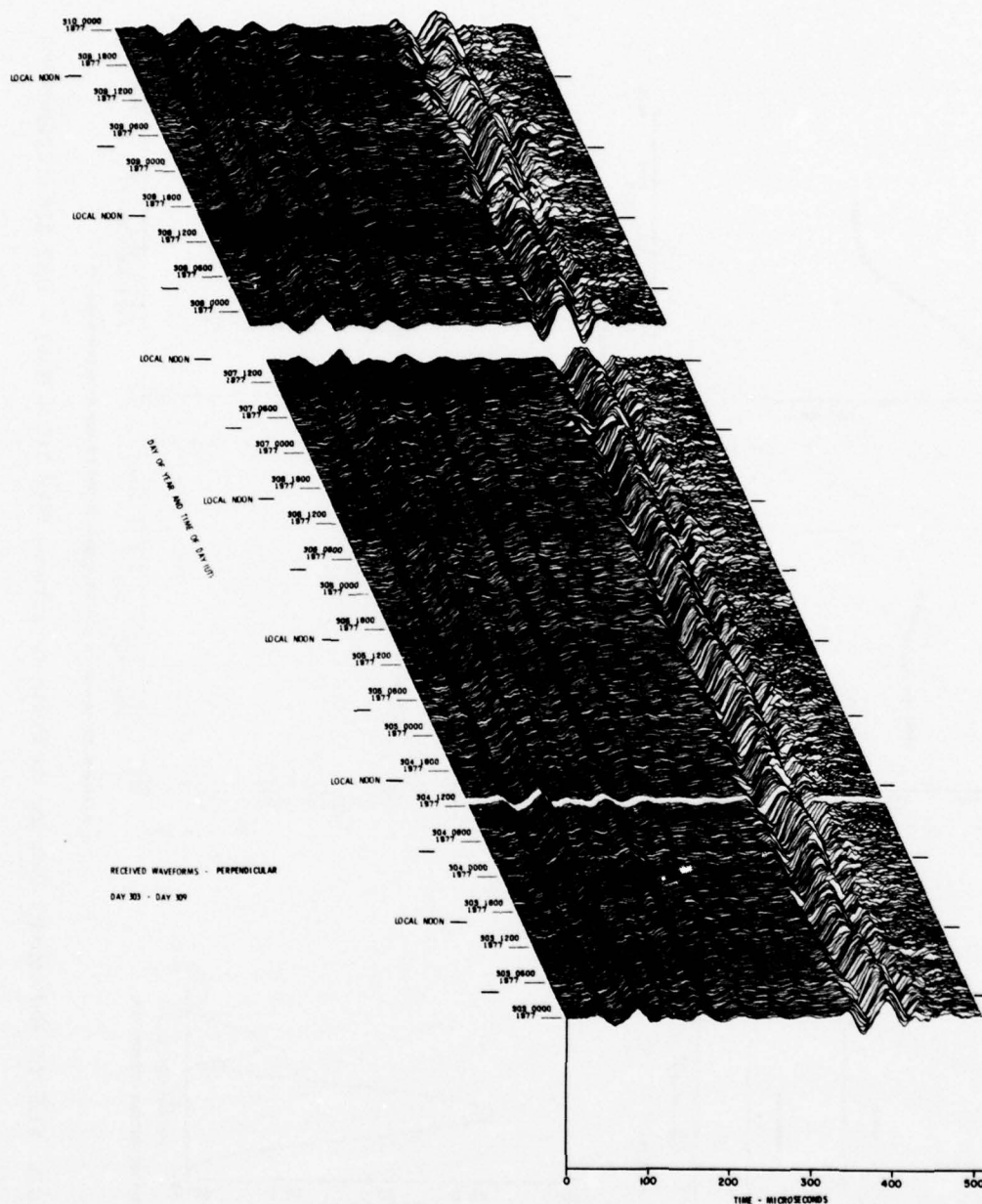


Figure 11. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 303 (30 Oct) - DAY 309 (5 Nov) 1977 (Cont)
 Part S. \perp Waveform Display

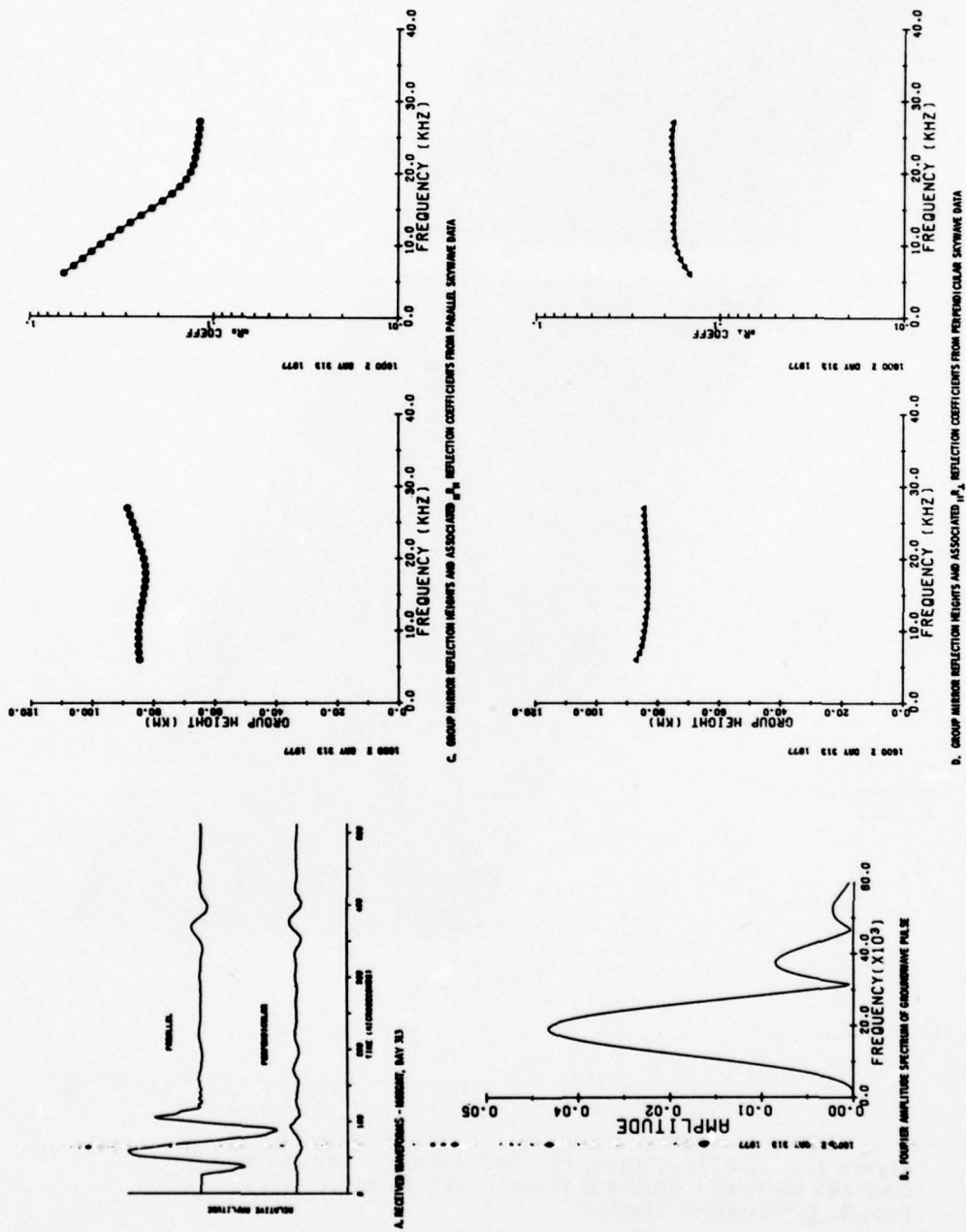


Figure 12. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 310 (6 Nov) - DAY 316 (12 Nov) 1977

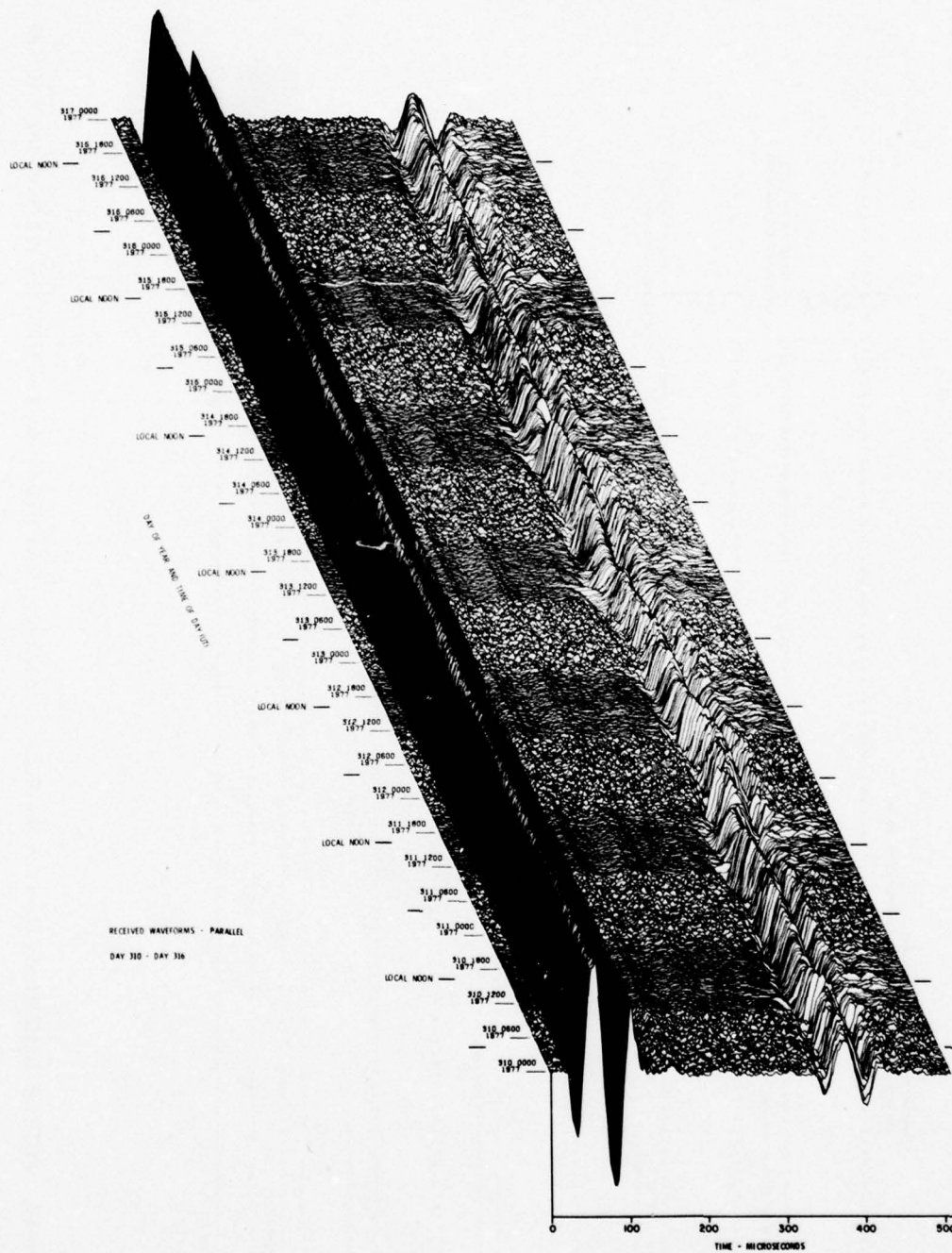


Figure 12. VLF/LF Reflectivity Data for the Polar Ionosphere,
DAY 310 (6 Nov) - DAY 316 (12 Nov) 1977 (Cont)
Part R. // Waveform Display

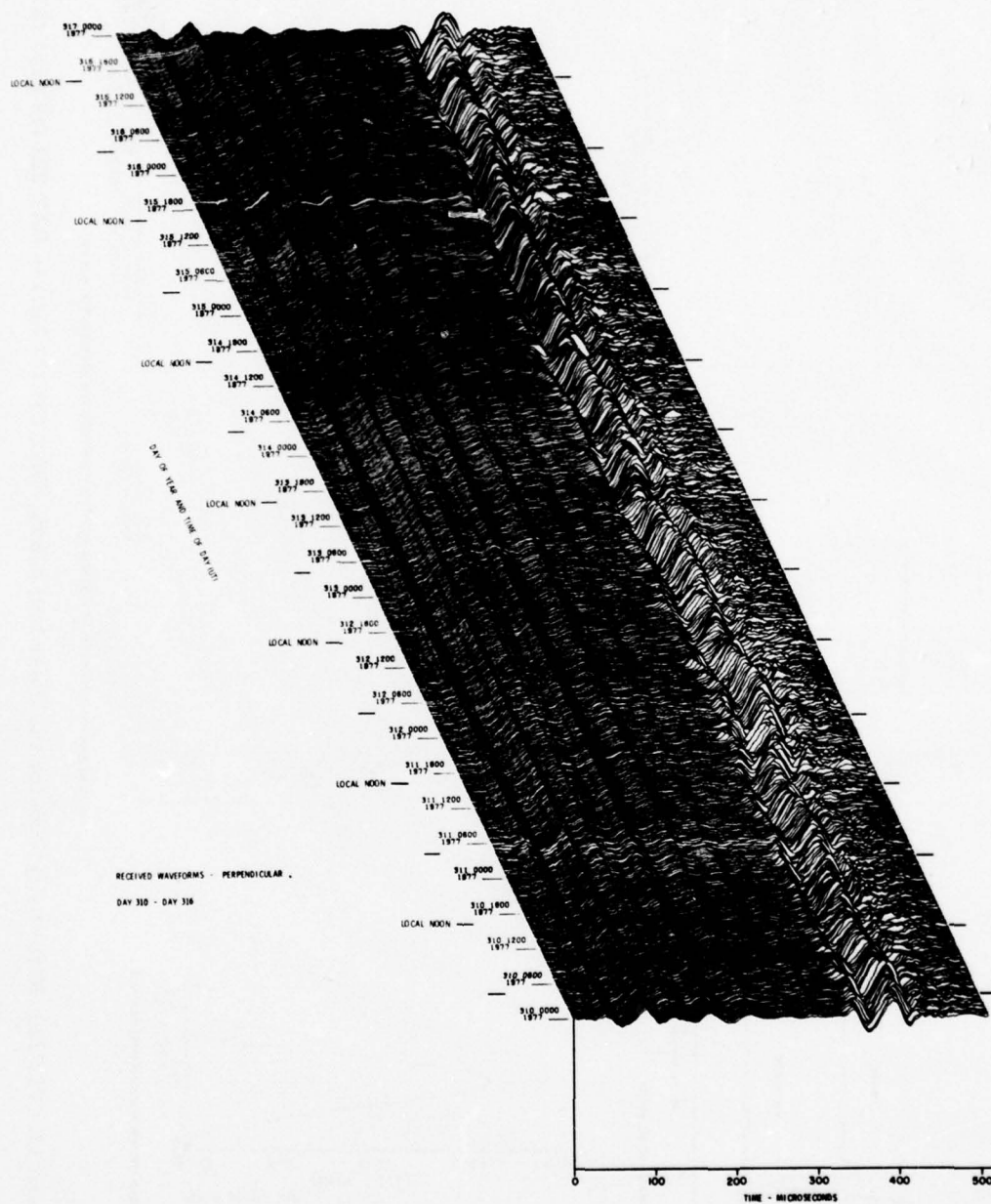


Figure 12. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 310 (6 Nov) - DAY 316 (12 Nov) 1977 (Cont)
 Part S. 1 Waveform Display

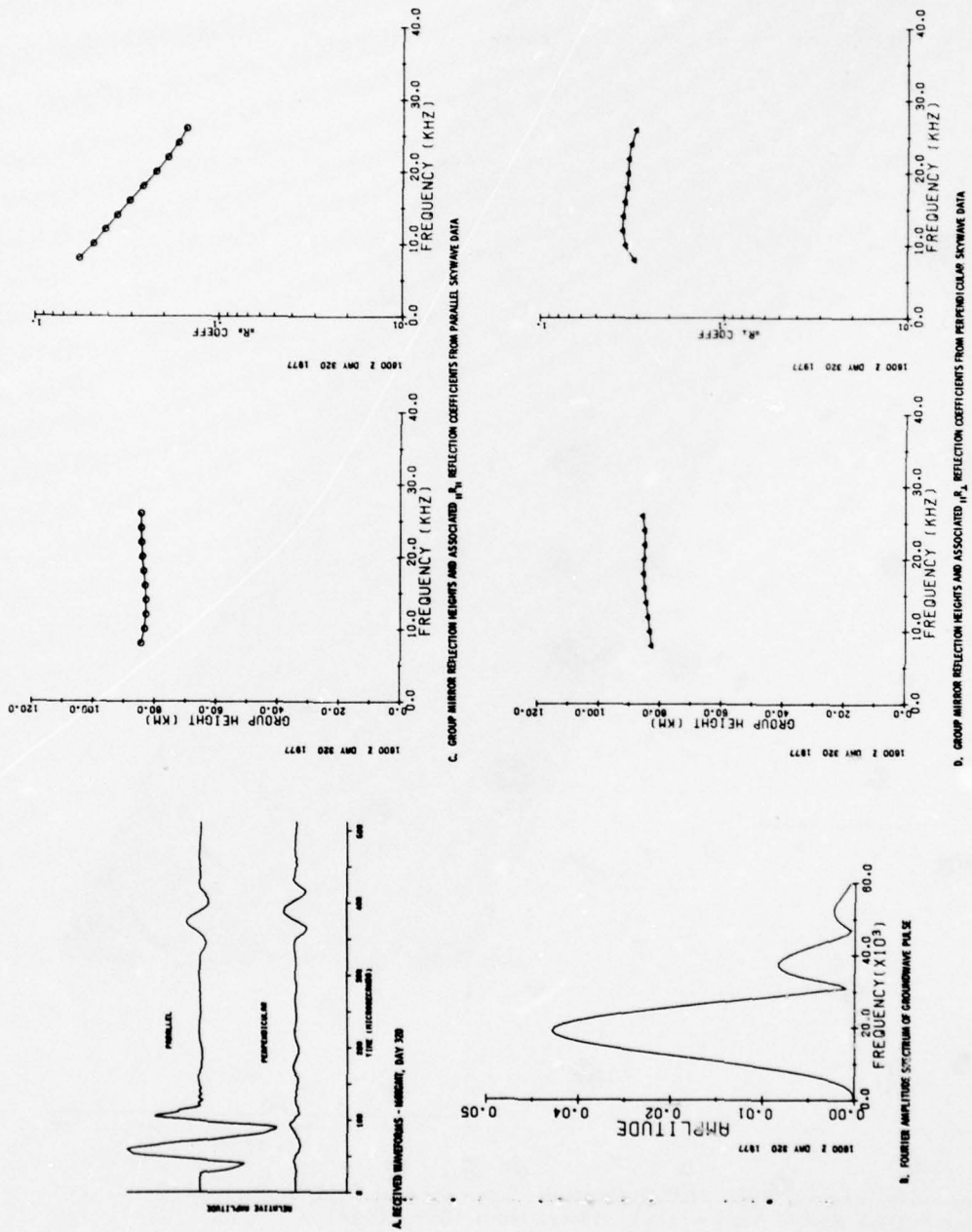


Figure 13. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 317 (13 Nov) - DAY 323 (19 Nov) 1977

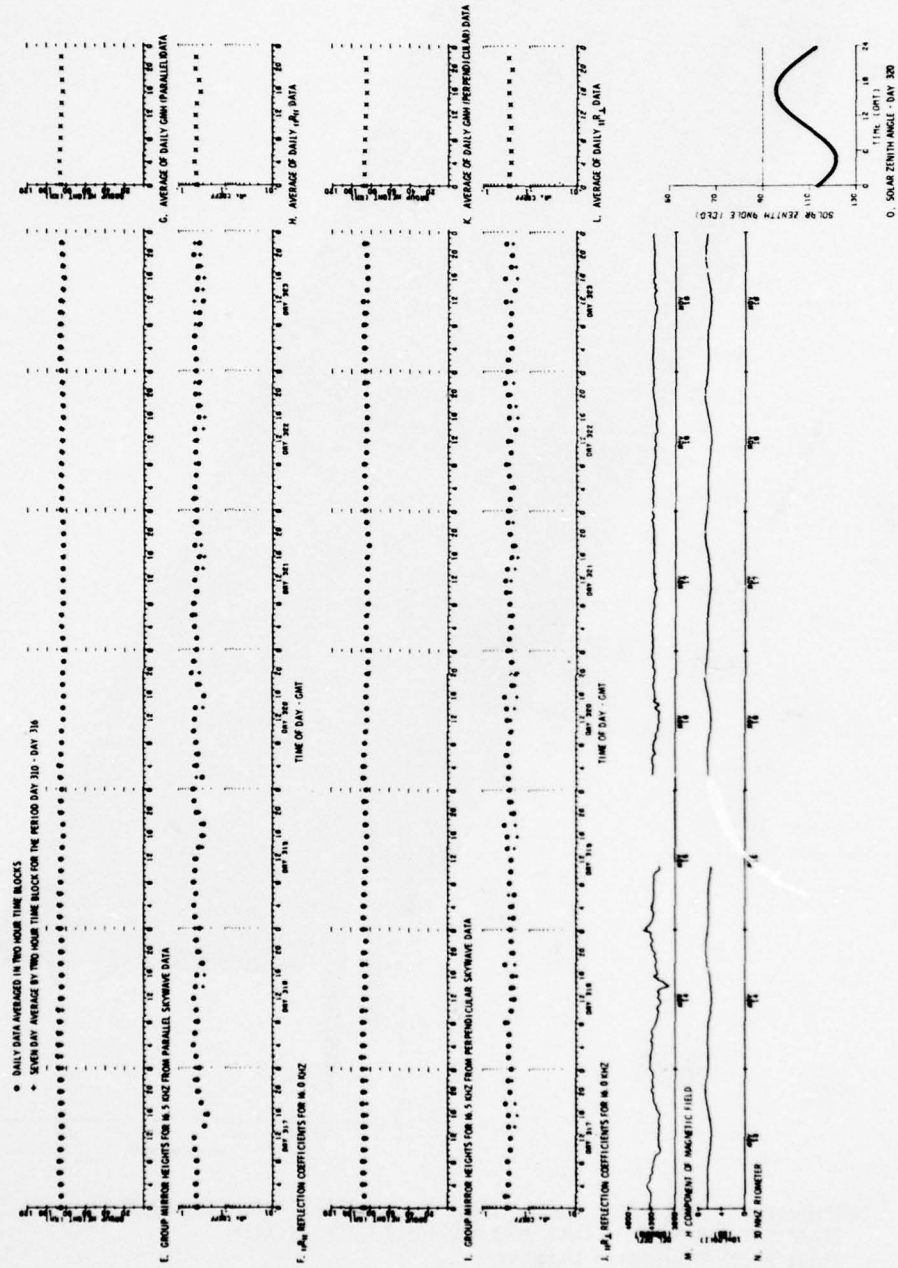


Figure 13. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 317 (13 Nov) - DAY 323 (19 Nov) 1977 (Cont)

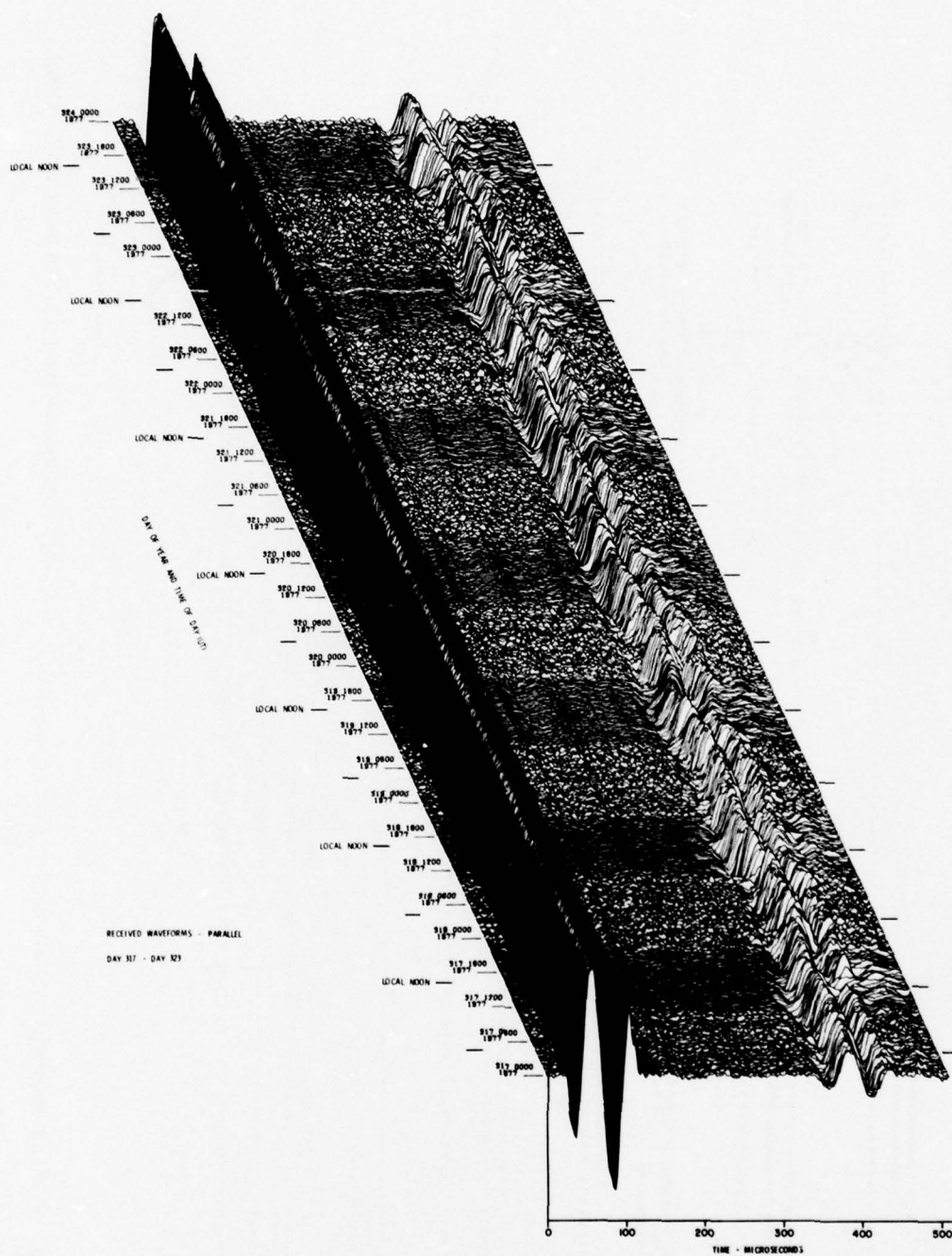


Figure 13. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 317 (13 Nov) - DAY 323 (19 Nov) 1977 (Cont)
 Part R. // Waveform Display

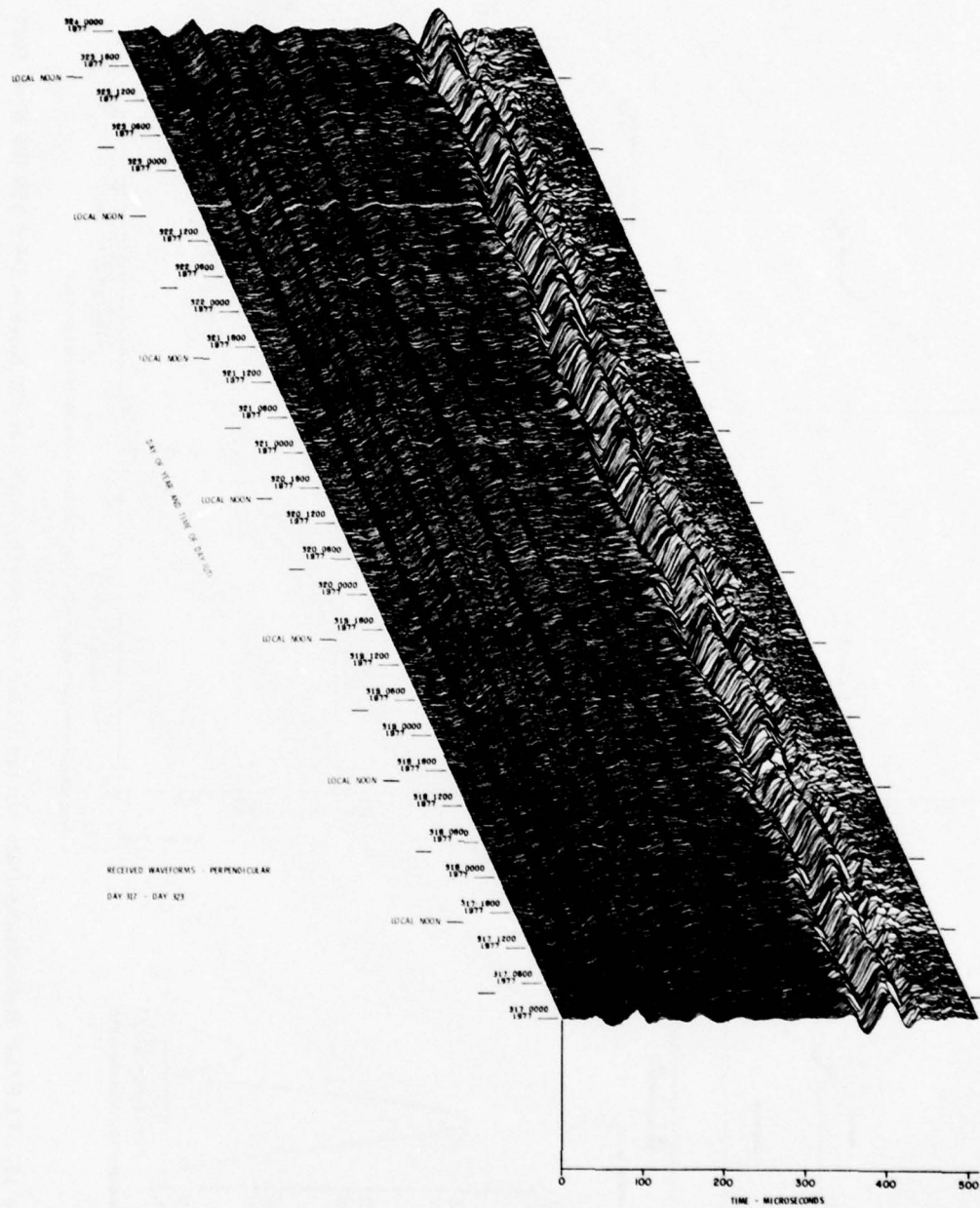


Figure 13. VLF/LF Reflectivity Data for the Polar Ionosphere,
DAY 317 (13 Nov) - DAY 323 (19 Nov) 1977 (Cont)
Part S. \perp Waveform Display

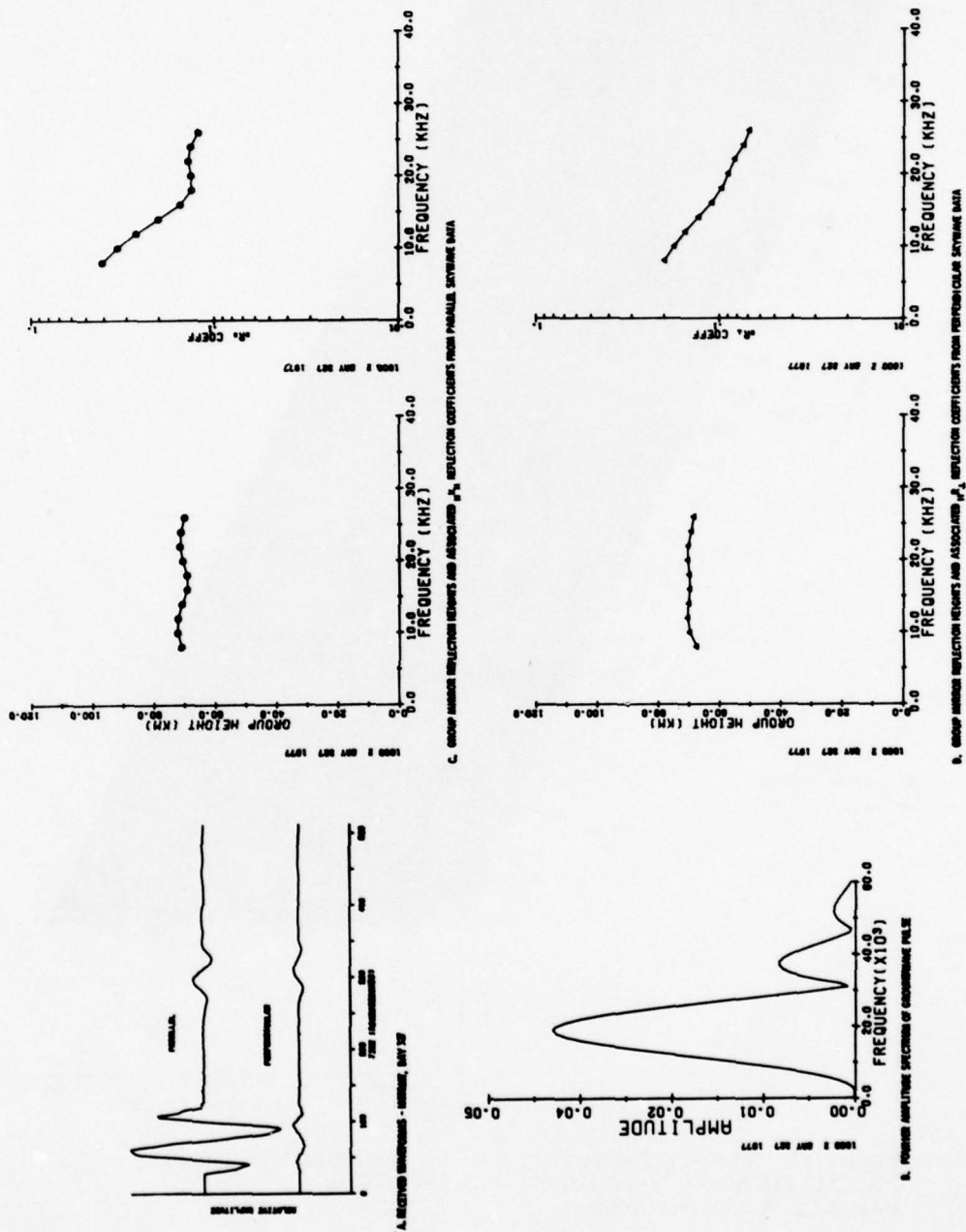


Figure 14. VLF/LF Reflectivity Data for the Polar Ionosphere, Day 324 (20 Nov) - Day 330 (26 Nov) 1977

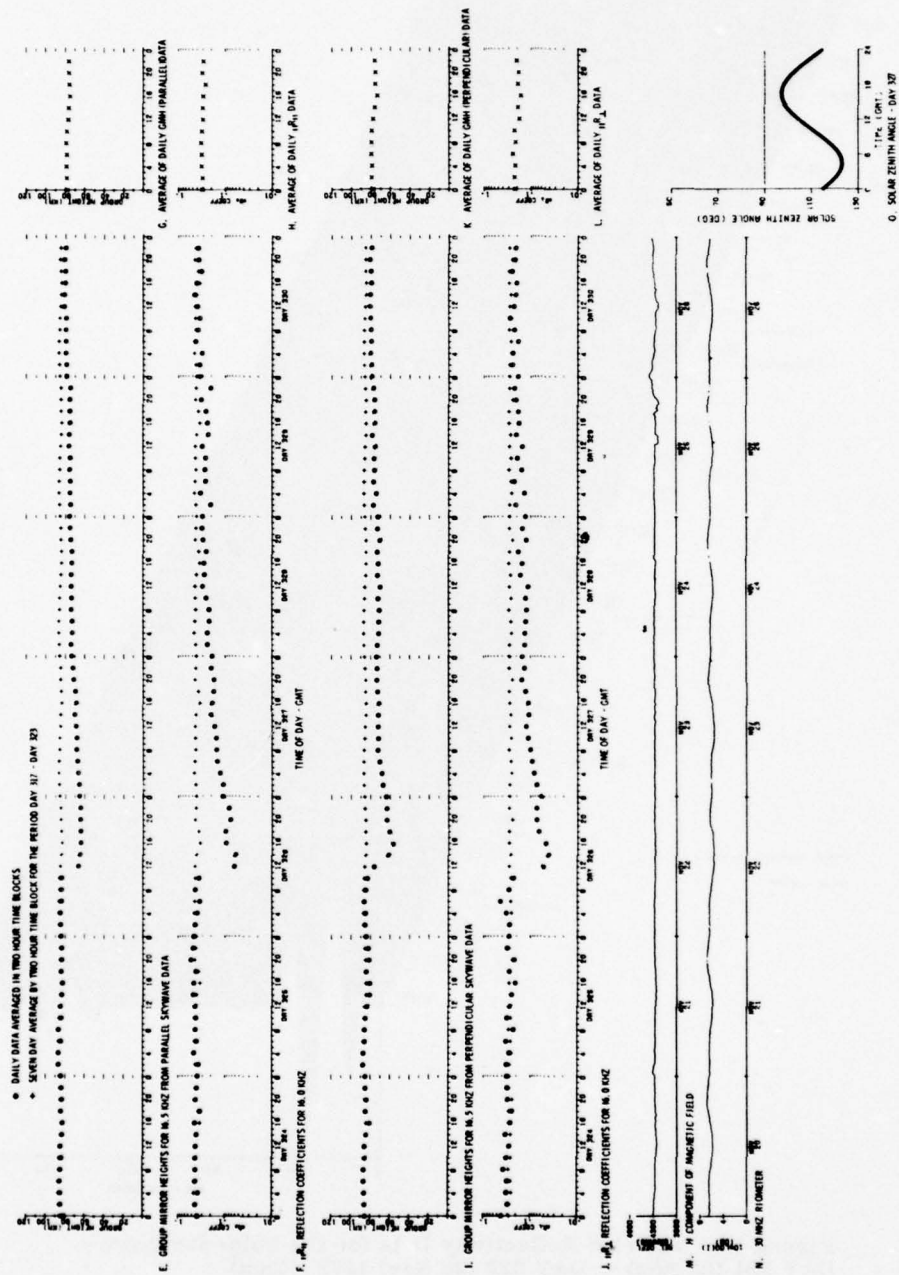


Figure 14. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 324 (20 Nov) - DAY 330 (26 Nov) 1977 (Cont)

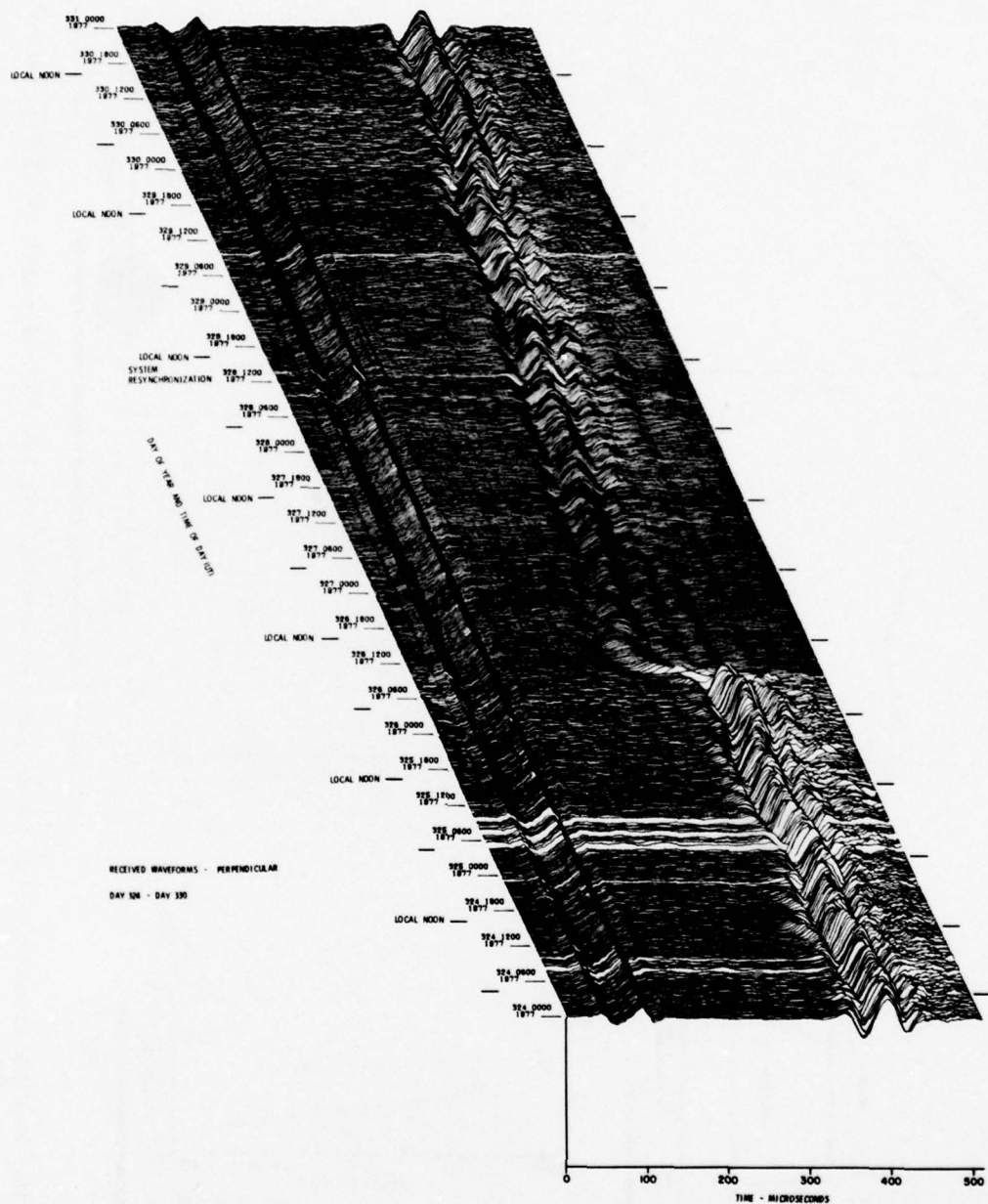


Figure 14. VLF/LF Reflectivity Data for the Polar Ionosphere,
DAY 324 (20 Nov) - DAY 330 (26 Nov) 1977 (Cont)
Part S. \perp Waveform Display

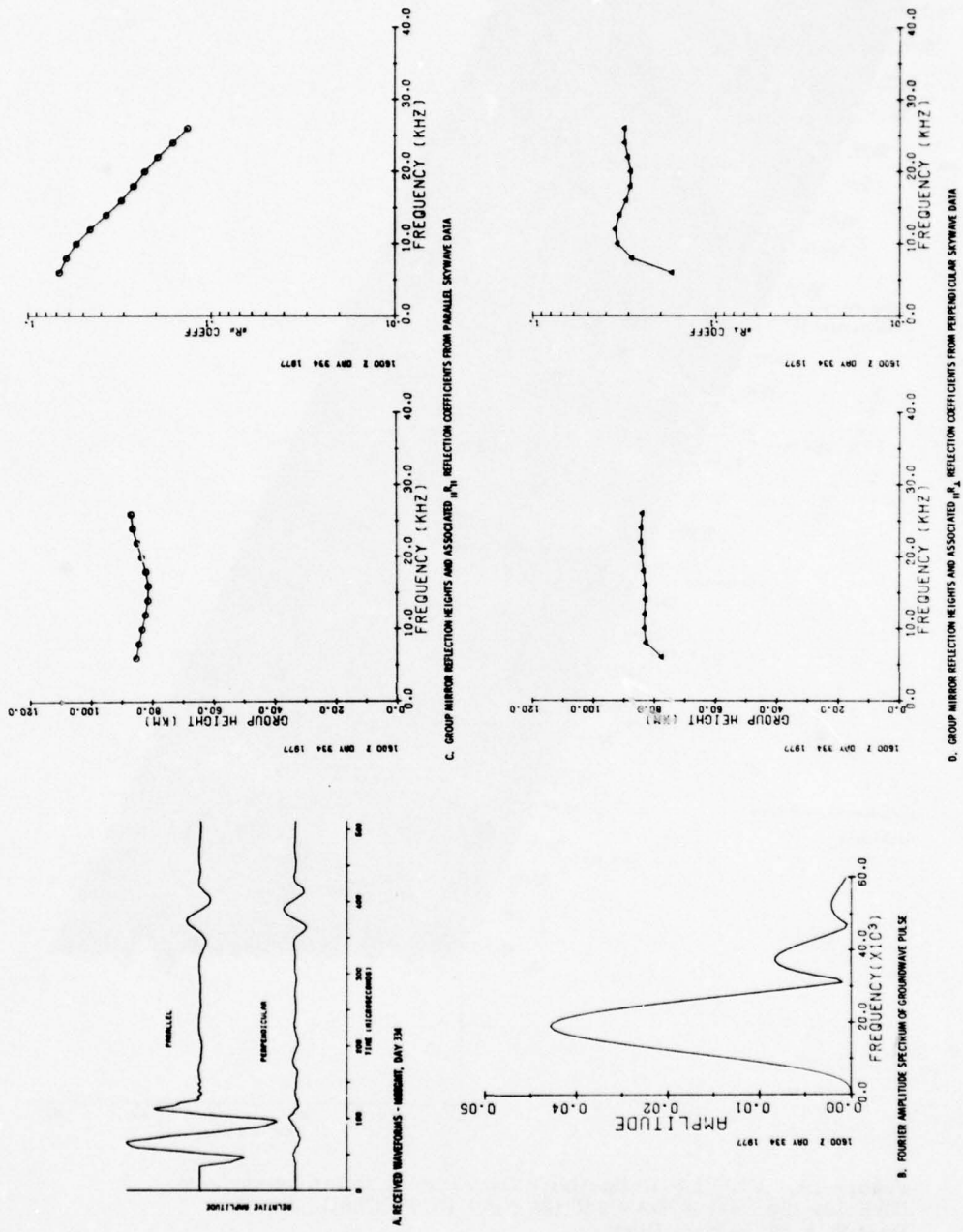


Figure 15. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 331 (27 Nov) - DAY 337 (3 Dec) 1977 (Cont)

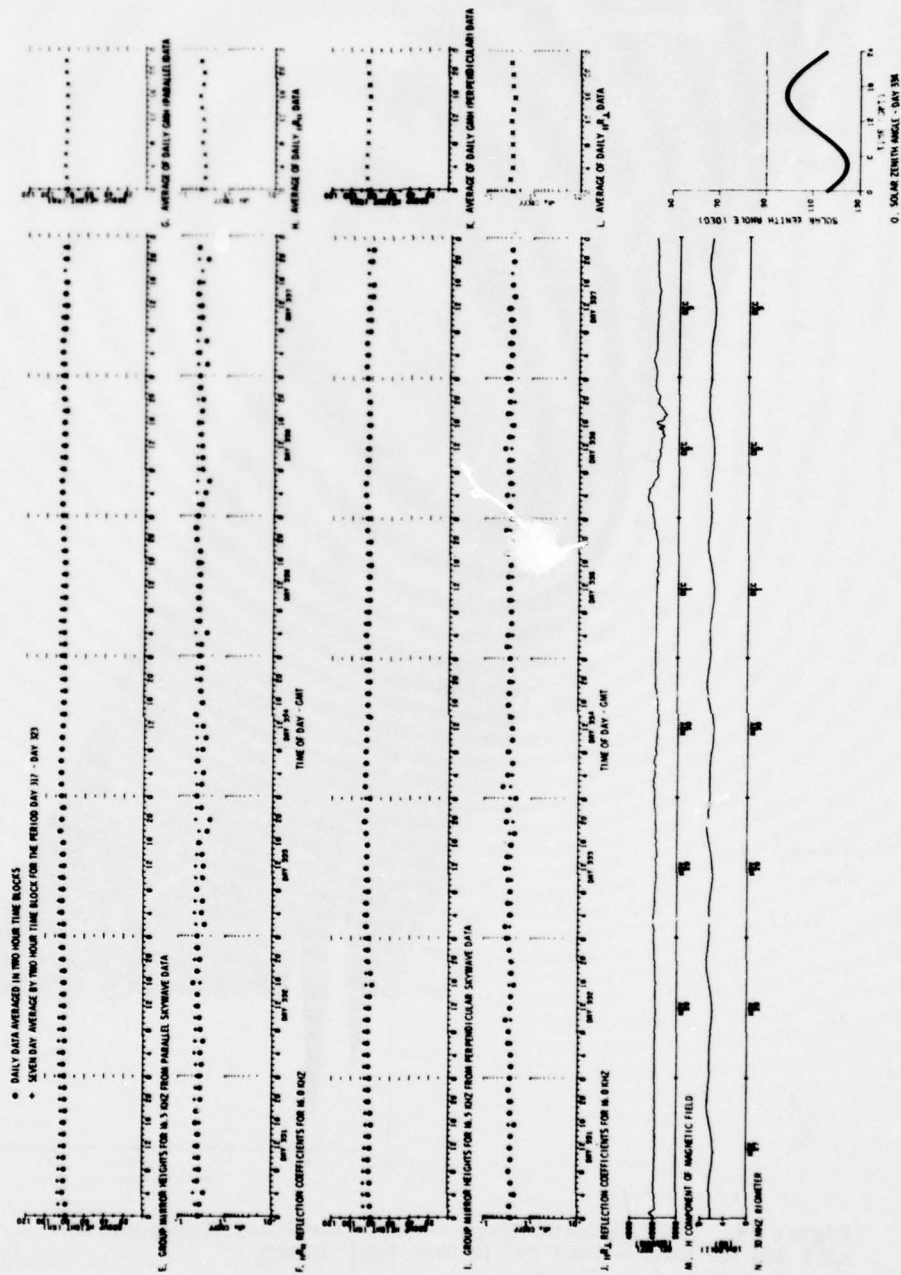


Figure 15. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 331 (27 Nov) - DAY 337 (3 Dec) 1977

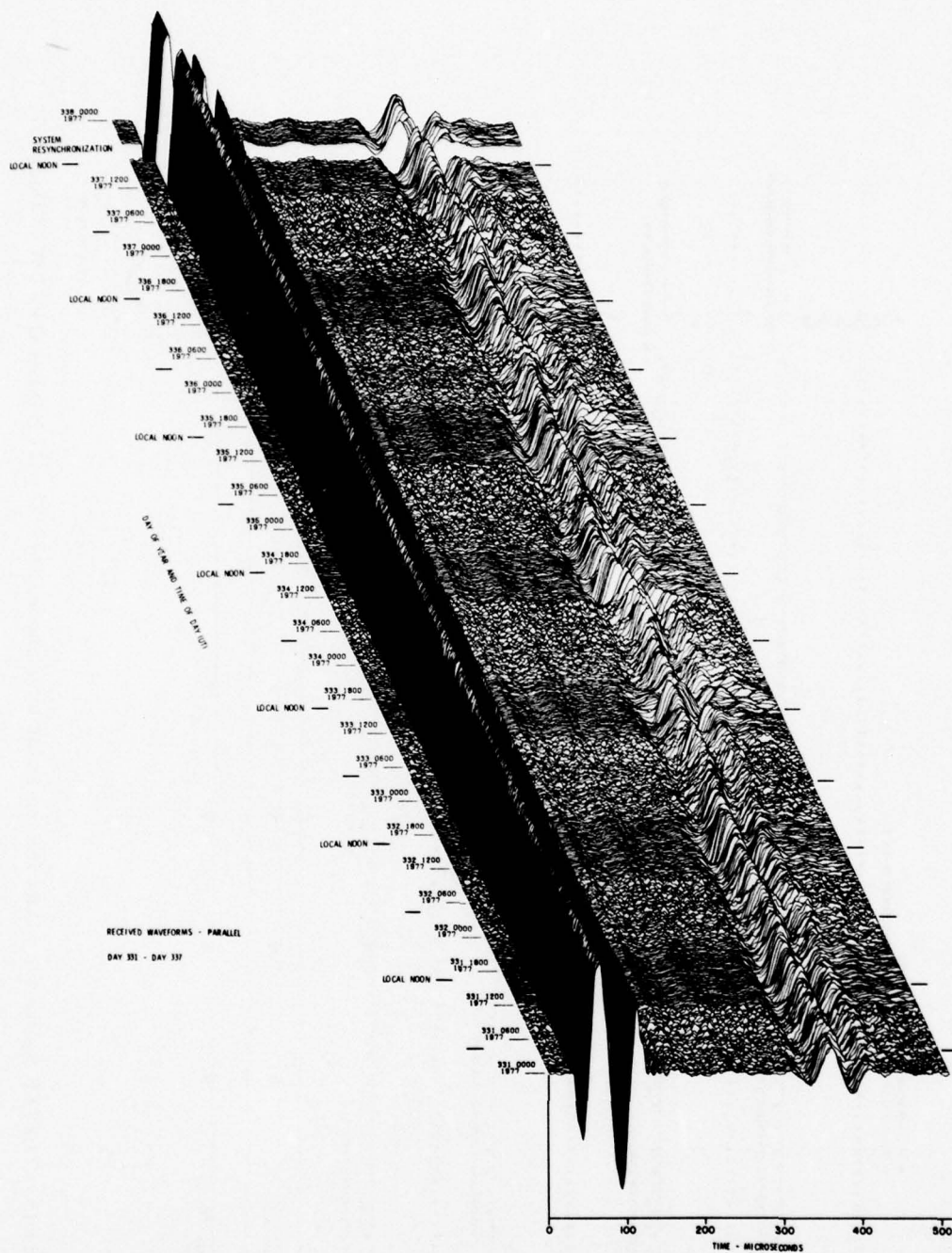


Figure 15. VLF/LF Reflectivity Data for the Polar Ionosphere,
DAY 331 (27 Nov) - DAY 337 (3 Dec) 1977 (Cont)
Part R. //Waveform Display

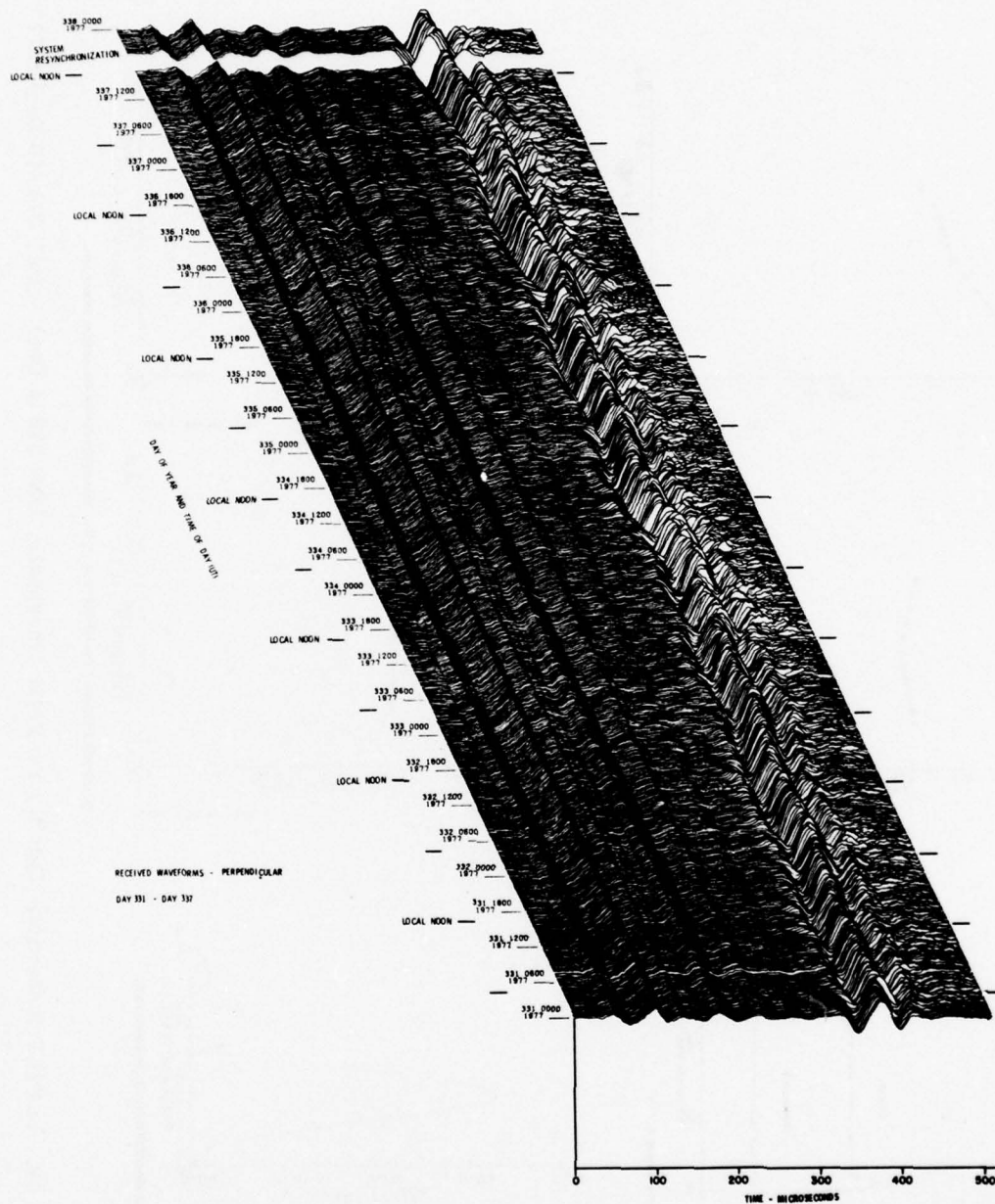


Figure 15. VLF/LF Reflectivity Data for the Polar Ionosphere,
DAY 331 (27 Nov) - DAY 337 (3 Dec) 1977 (Cont)
Part S. Waveform Display

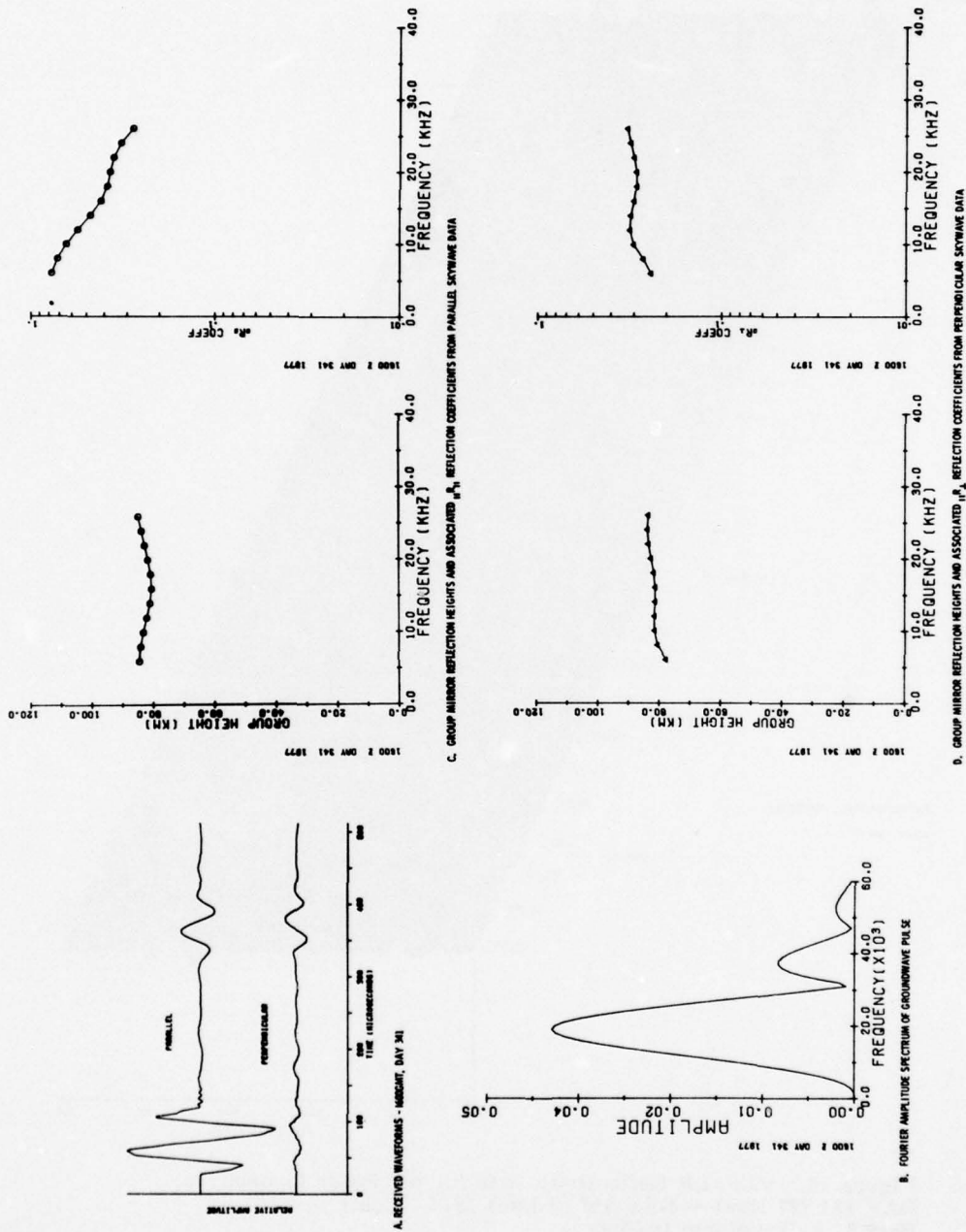


Figure 16. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 338 (4 Dec) - DAY 344 (10 Dec) 1977

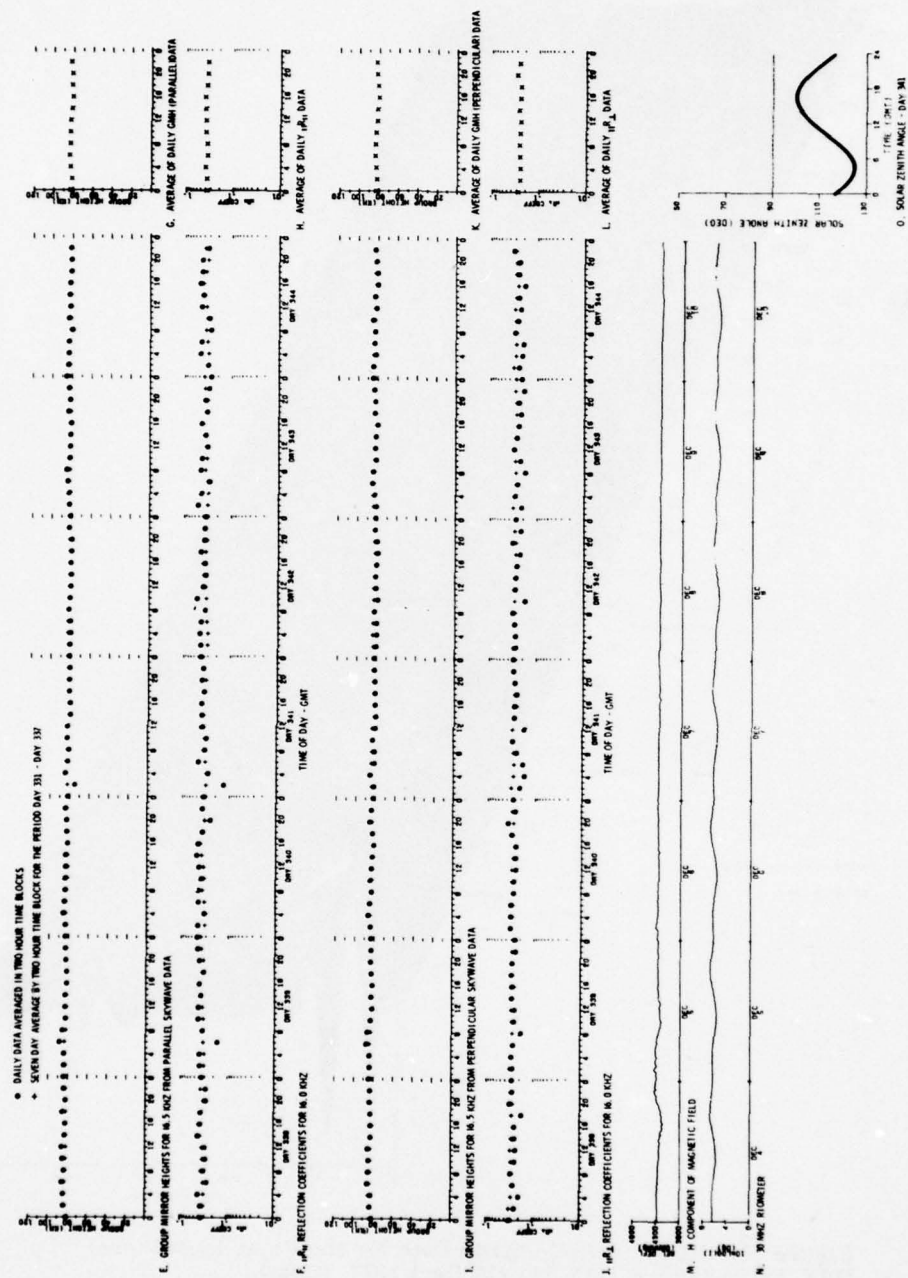


Figure 16. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 338 (4 Dec) - DAY 344 (10 Dec) 1977 (Cont)

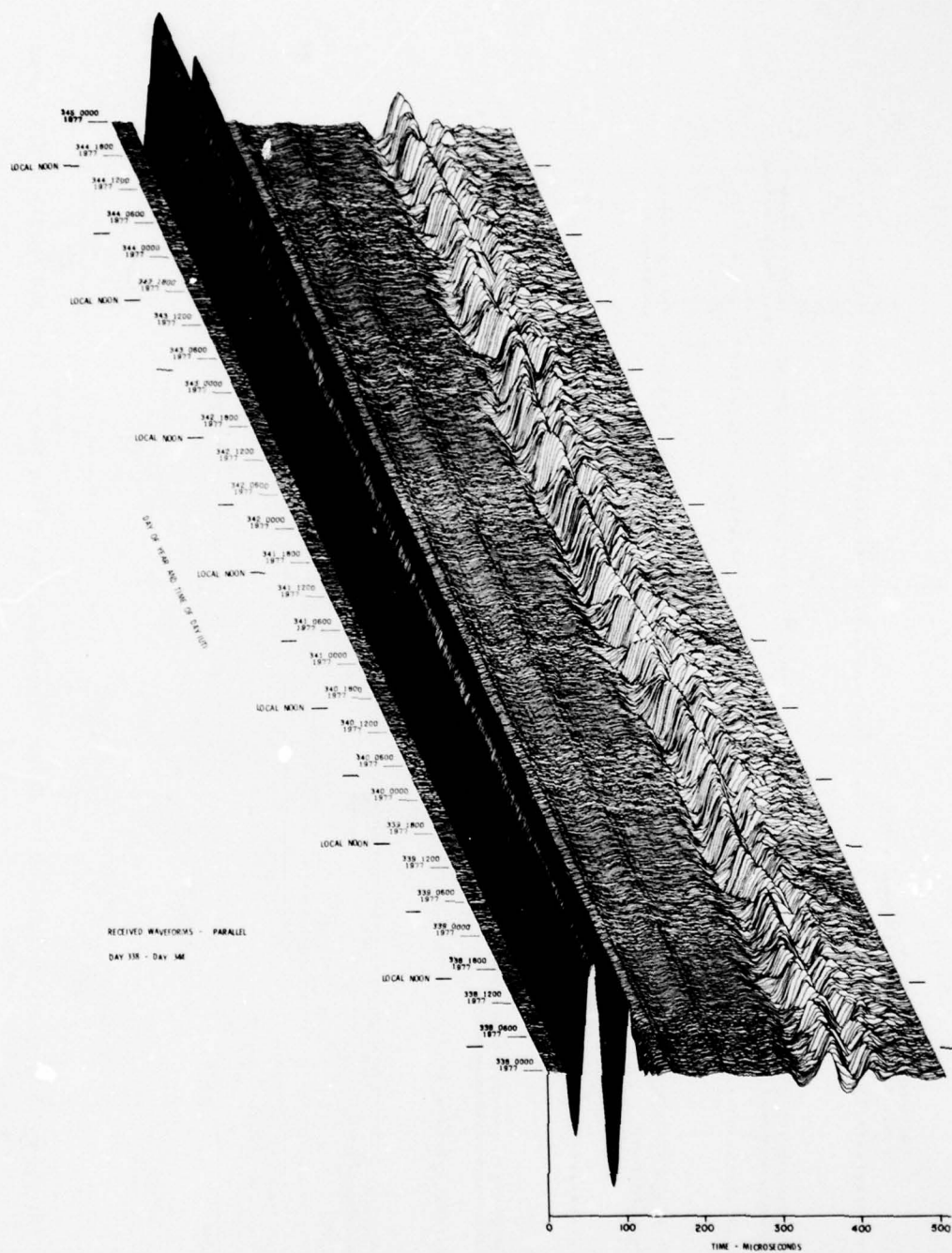


Figure 16. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 338 (4 Dec) - DAY 344 (10 Dec) 1977 (Cont)
 Part R. || Waveform Display

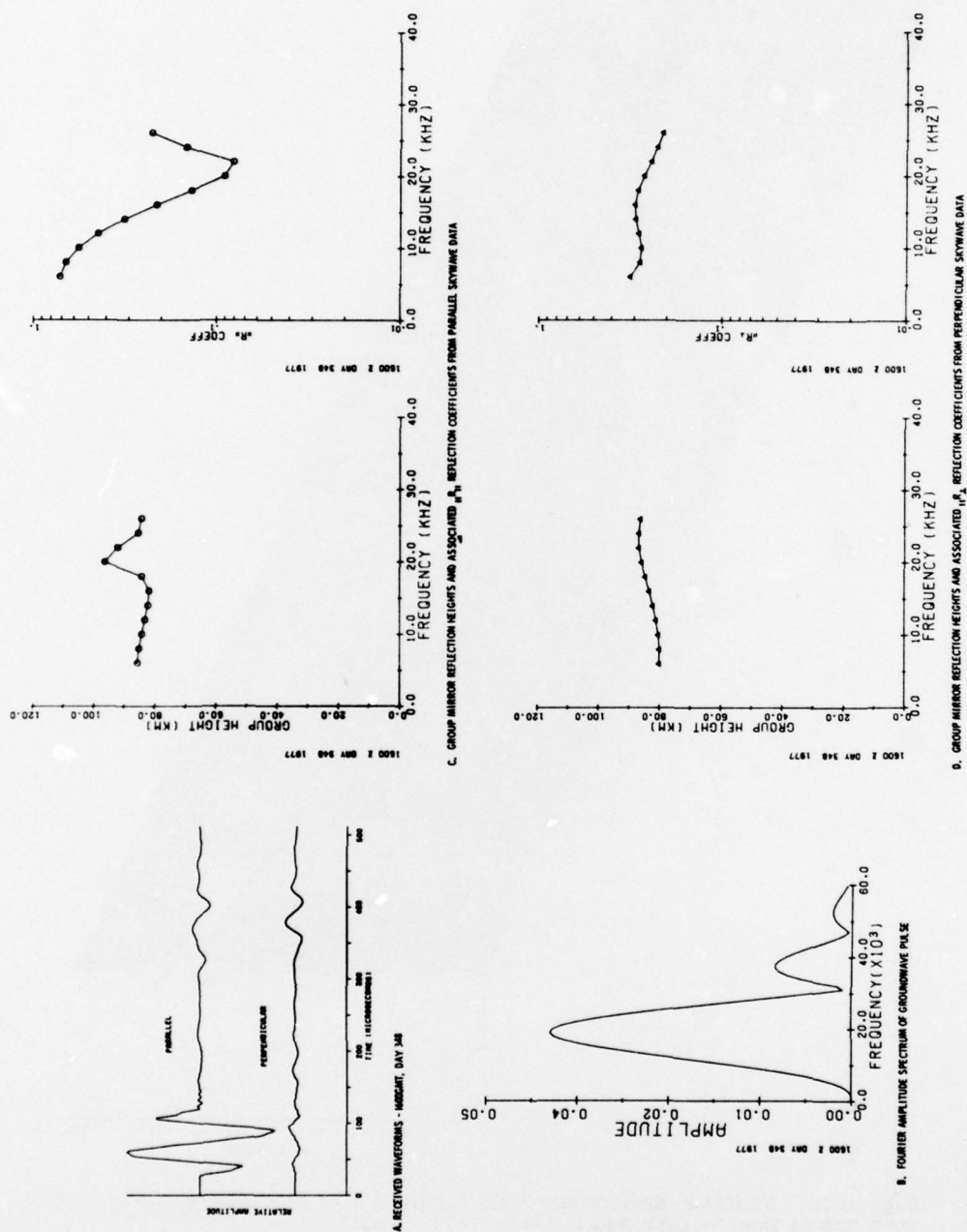


Figure 17. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 345 (11 Dec) - DAY 351 (17 Dec) 1977

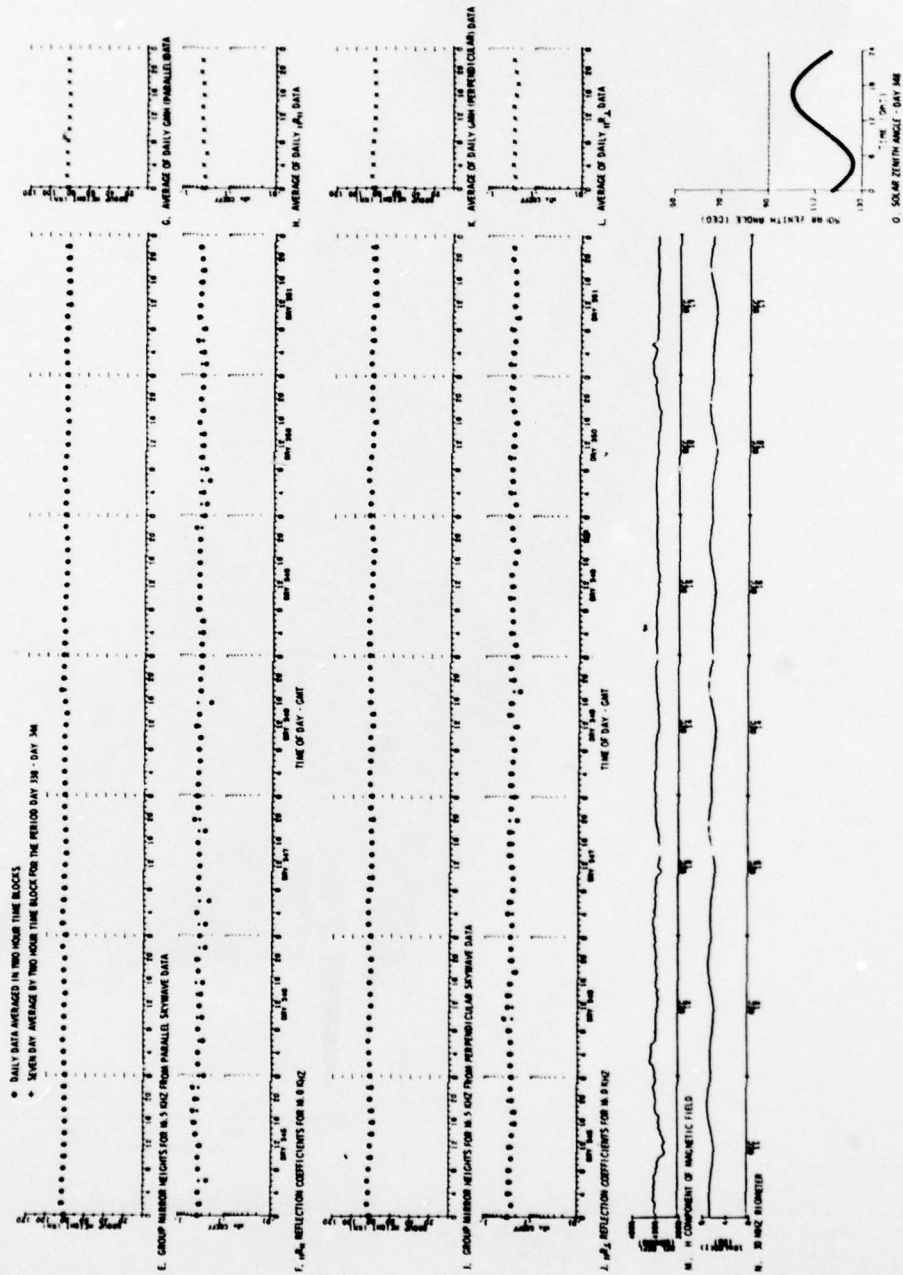


Figure 17. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 345 (11 Dec) - DAY 351 (17 Dec) 1977 (Cont)

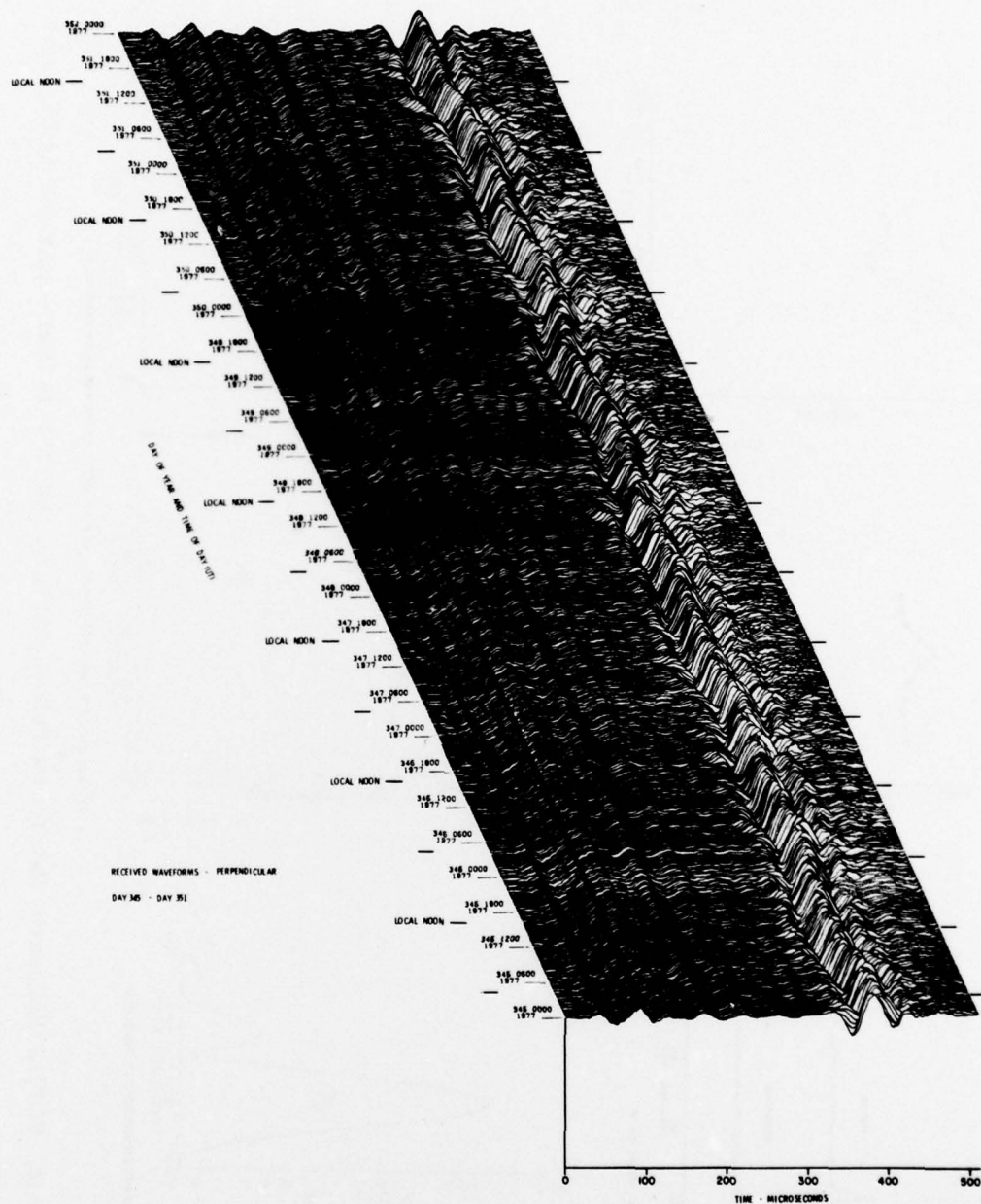


Figure 17. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 345 (11 Dec) - DAY 351 (17 Dec) 1977 (Cont)
 Part S. \perp Waveform Display

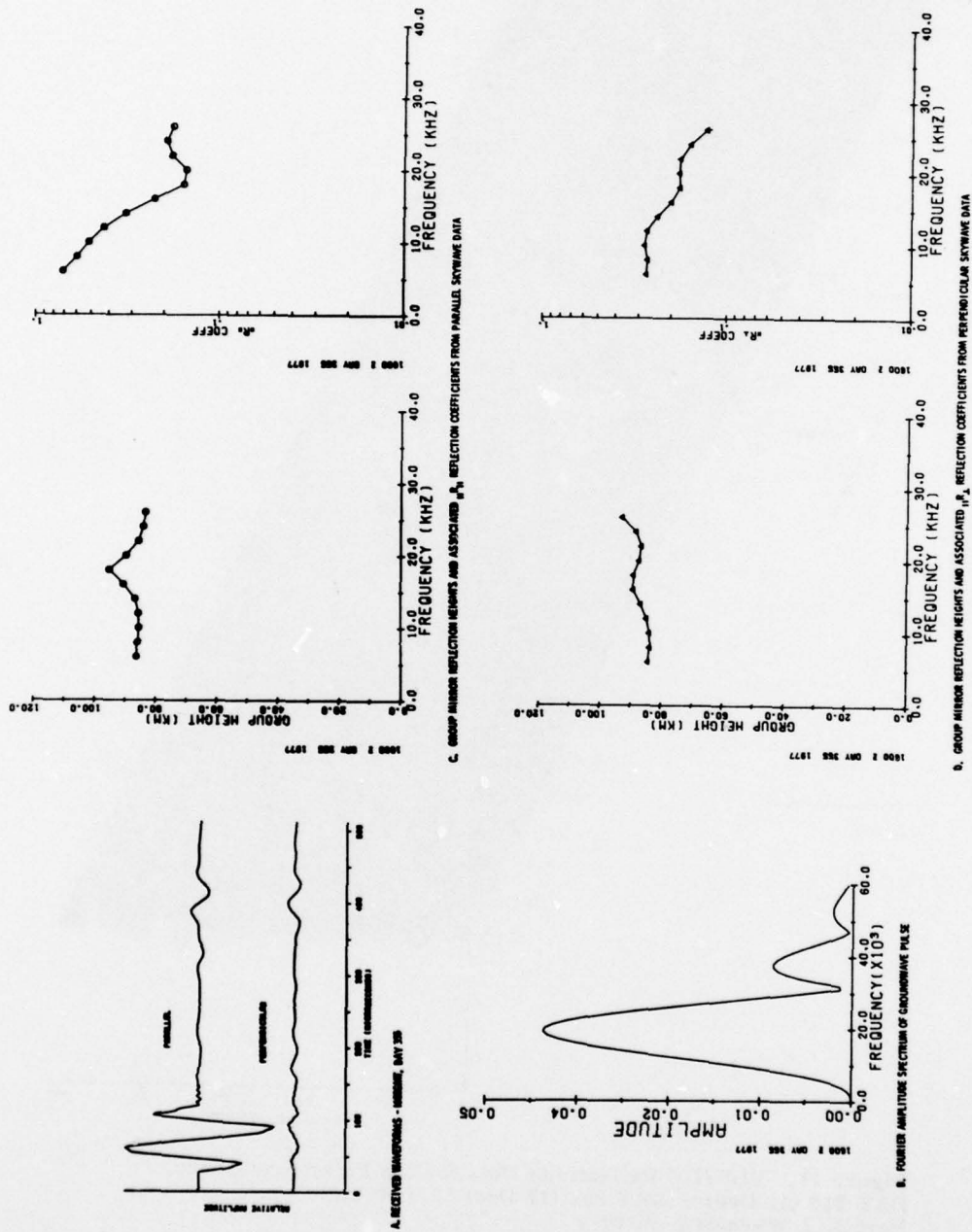


Figure 18. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 352 (18 Dec) - DAY 358 (24 Dec) 1977

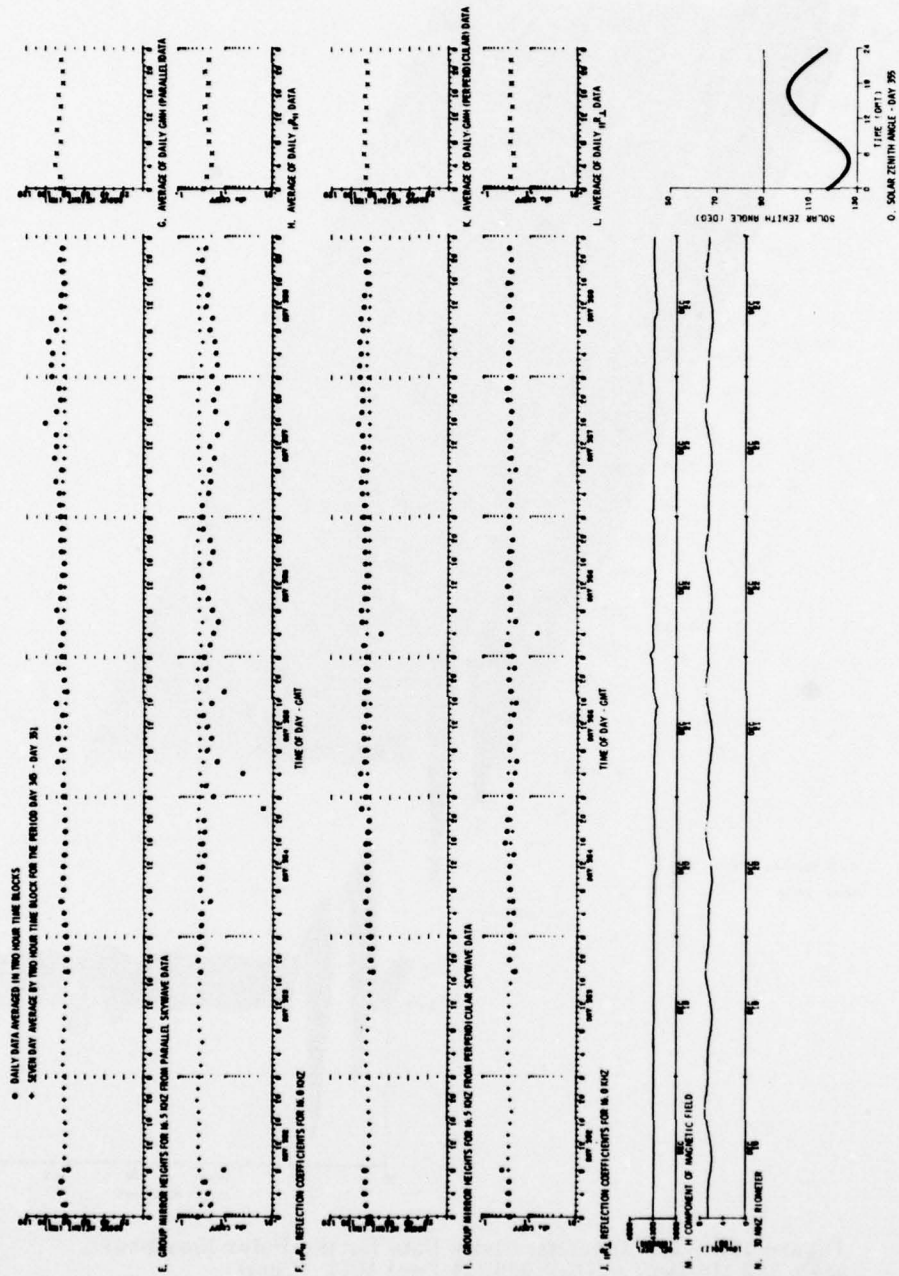


Figure 18. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 352 (18 Dec) - DAY 358 (24 Dec) 1977 (Cont)

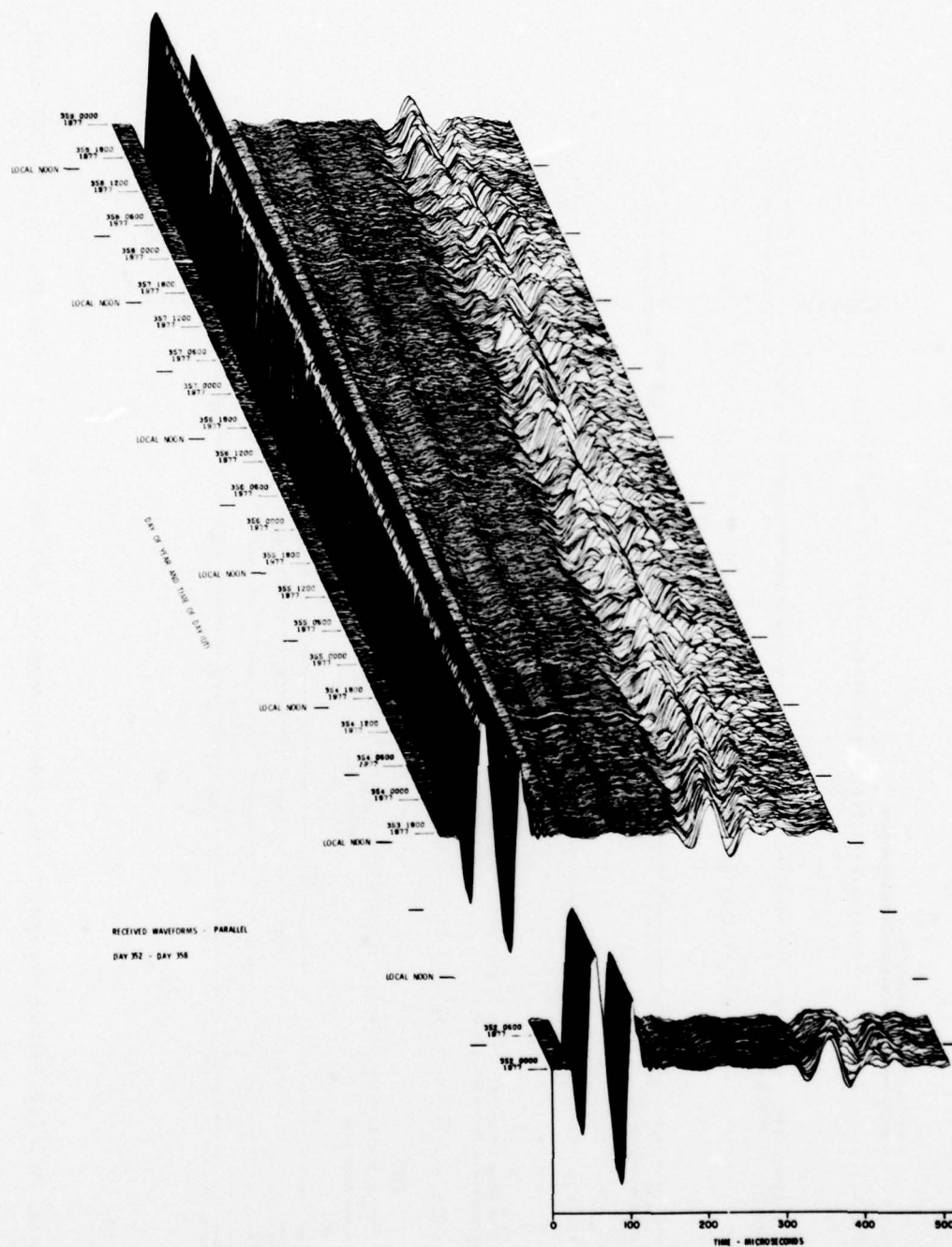


Figure 18. VLF/LF Reflectivity Data for the Polar Ionosphere,
DAY 352 (18 Dec) - DAY 358 (24 Dec) 1977 (Cont)
Part R. || Waveform Display

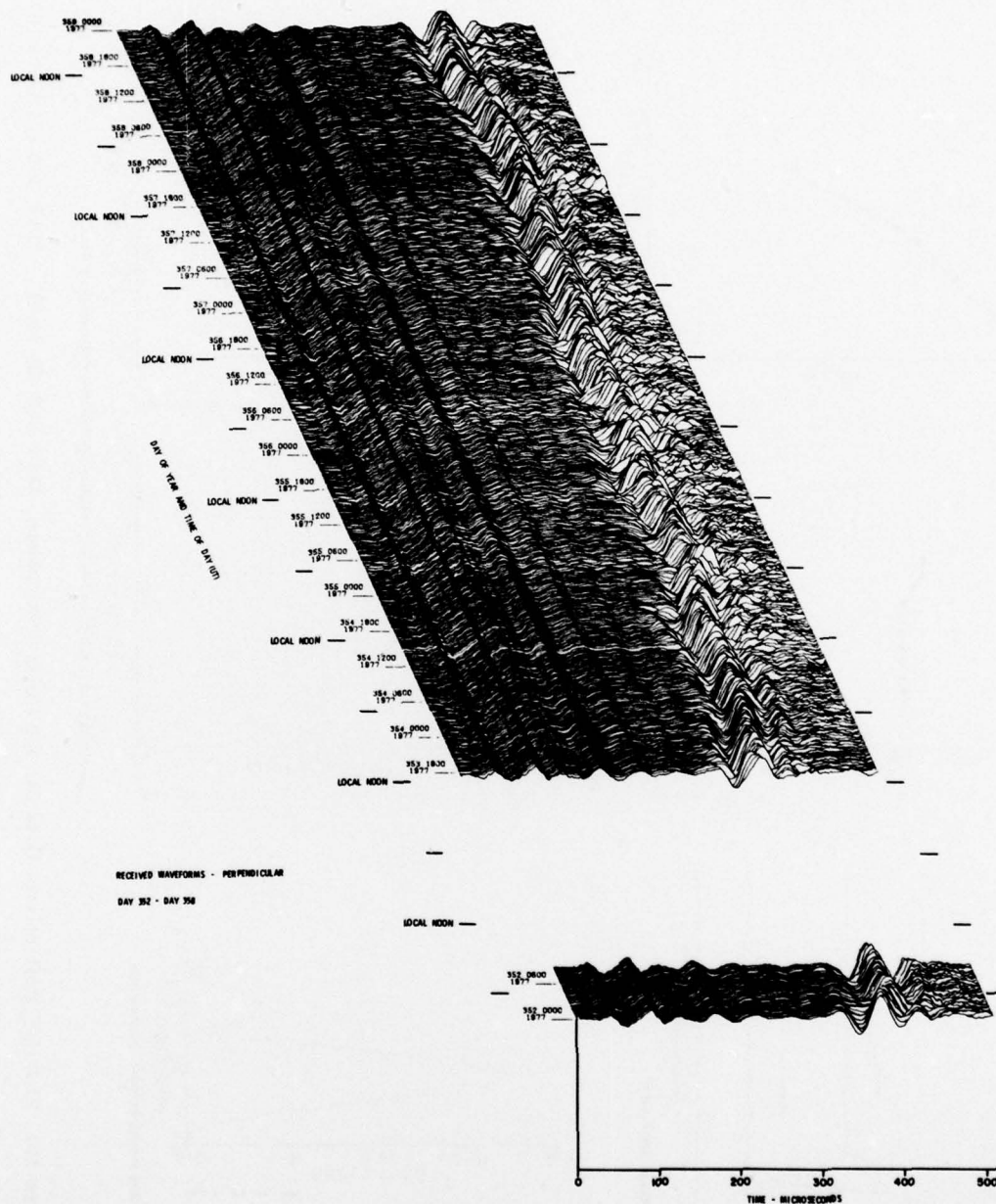


Figure 18. VLF/LF Reflectivity Data for the Polar Ionosphere,
 DAY 352 (18 Dec) - DAY 358 (24 Dec) 1977 (Cont)
 Part S. \perp Waveform Display

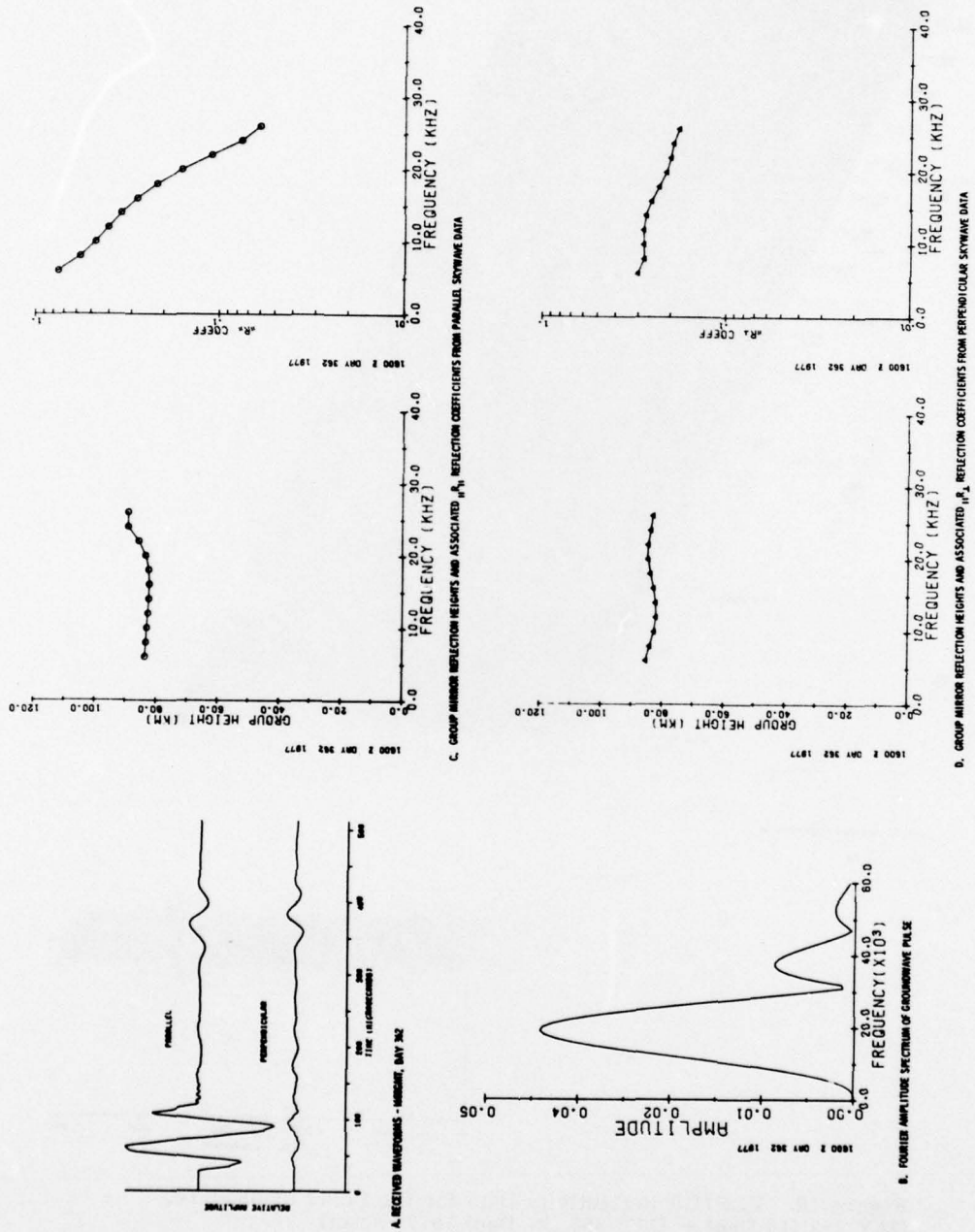


Figure 19. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 359 (25 Dec) - DAY 365 (31 Dec) 1977

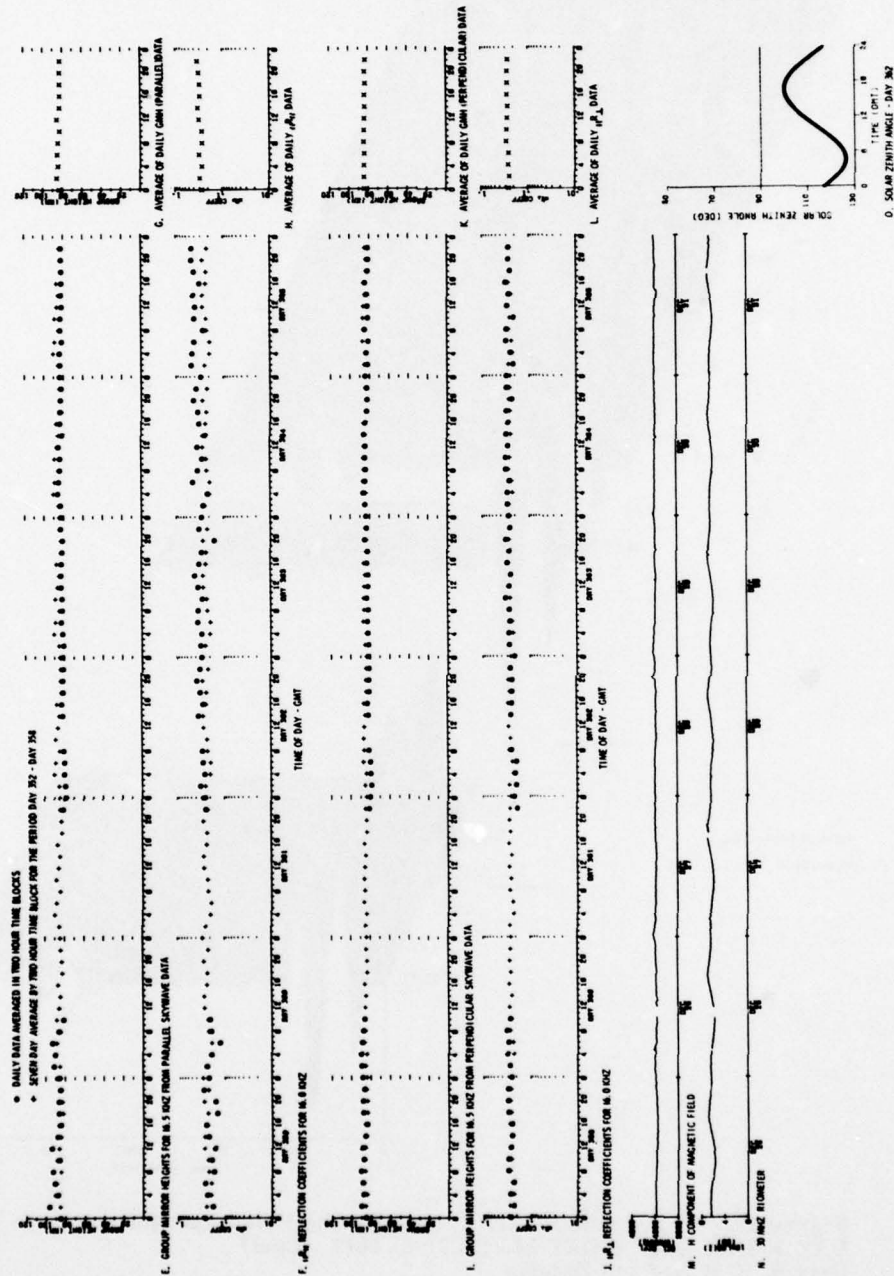


Figure 19. VLF/LF Reflectivity Data for the Polar Ionosphere, DAY 359 (25 Dec) - DAY 365 (31 Dec) 1977 (Cont)

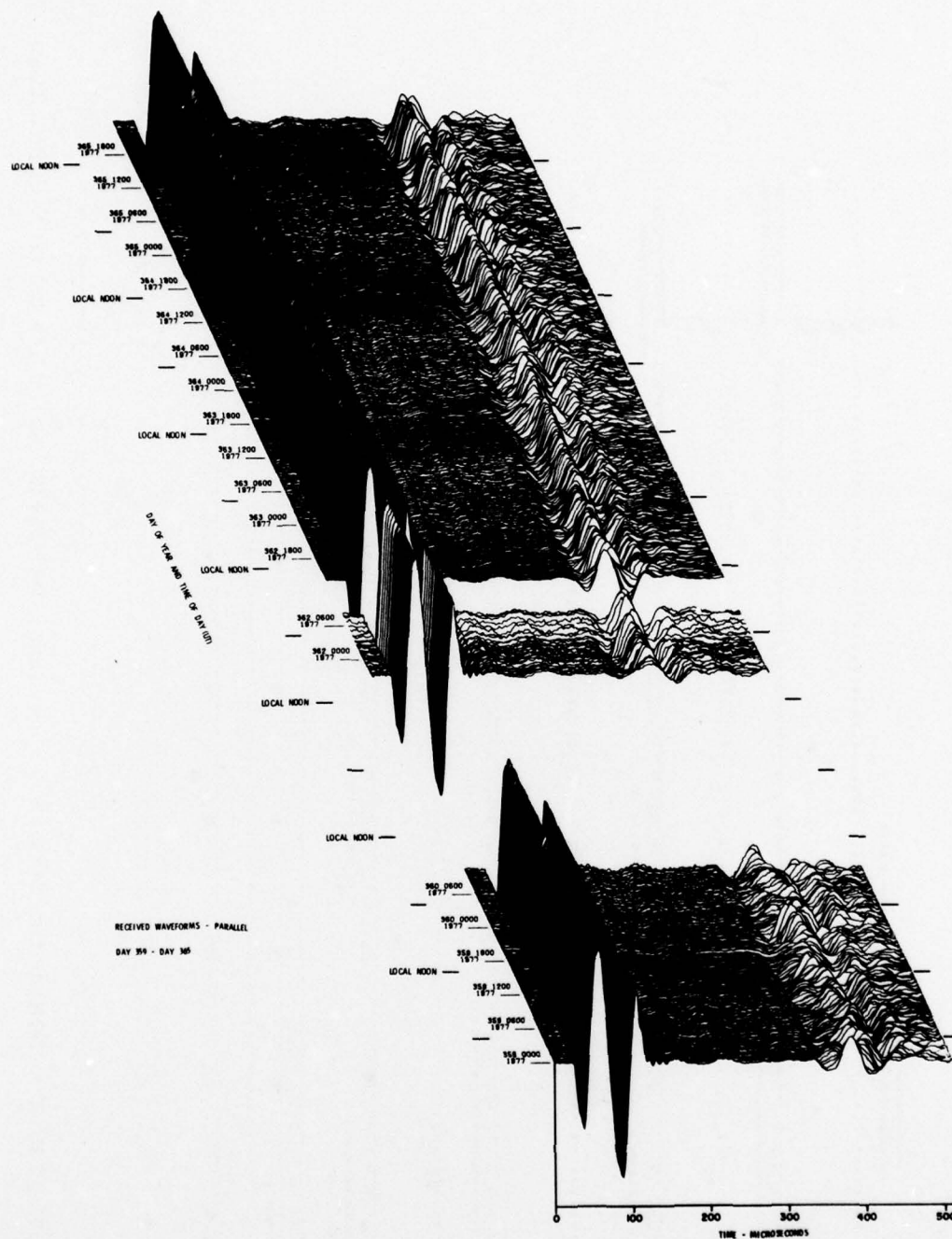


Figure 19. VLF/LF Reflectivity Data for the Polar Ionosphere,
DAY 359 (25 Dec) — DAY 365 (31 Dec) 1977 (Cont)
Part R. Waveform Display

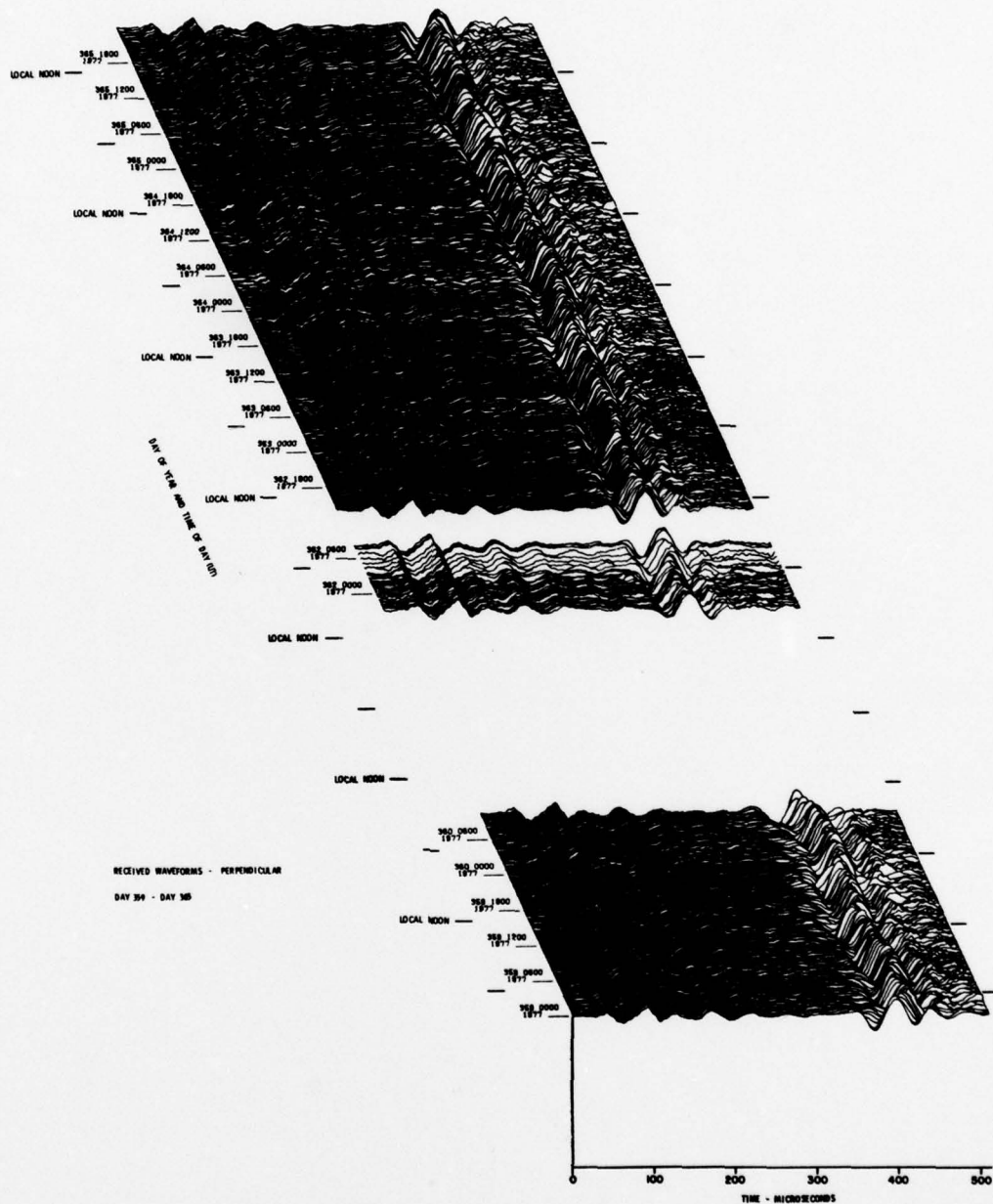
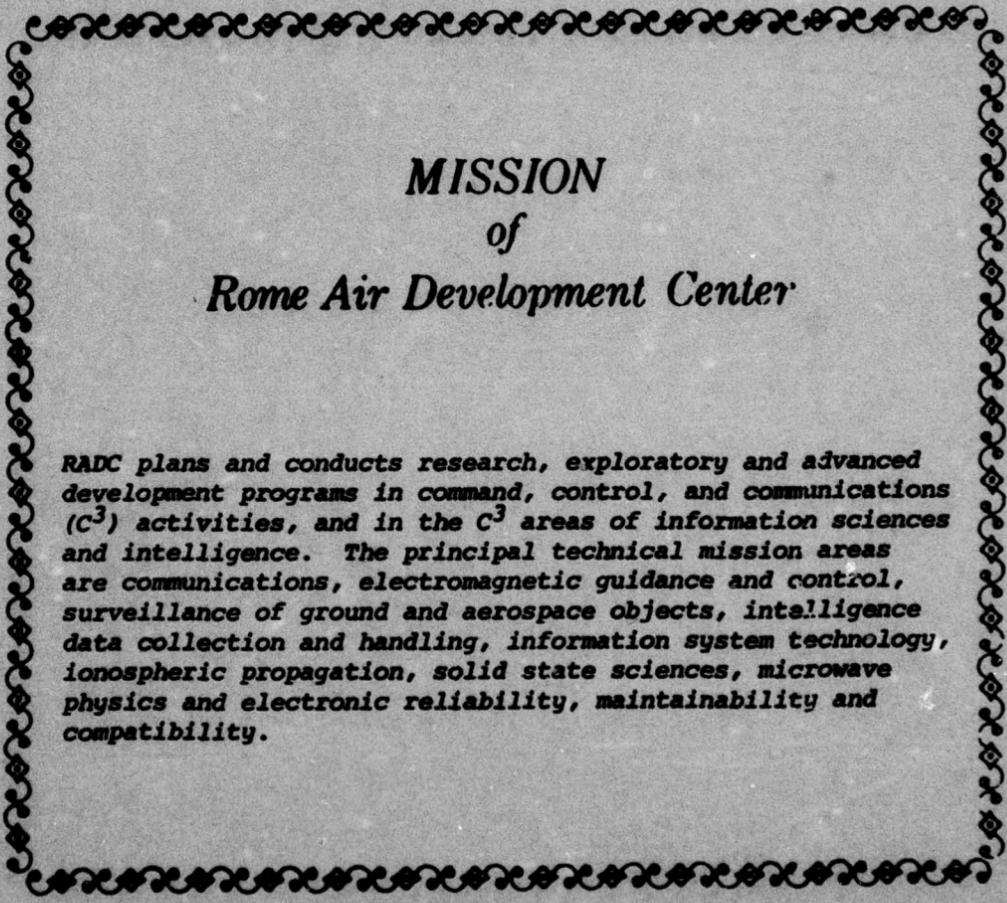


Figure 19. VLF/LF Reflectivity Data for the Polar Ionosphere,
DAY 359 (25 Dec) - DAY 365 (31 Dec) 1977 (Cont)
Part S. 1 Waveform Display



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